AN APPLICATION OF HOLOGRAPHIC INTERFEROMETRY TO GUN BARREL EROSION

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THESIS

AN APPLICATION OF HOLOGRAPHIC INTERFEROMETRY TO GUN BARREL EROSION

by

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December 1974

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An Application of Holographic Interferometry
to Gun Barrel Erosion

by

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Lieutenant, United States Navy
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ABSTRACT

Real time holographic interferometry has recently been applied to many engineering areas. This study presents the development and investigation of a technique to predict gun barrel wear by examining the barrel erosion through the use of real time holographic interferometry. It was determined that the proposed technique was probably not feasible due to the extreme sensitivity of real time holography to any change in surface microstructures and due to the difficulty of precise relocation of the object. During investigation of the proposed technique, holographic data addressing the problem of general translation of an object was acquired and is also reported.

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I. INTRODUCTION

The precise measurement of gun barrel erosion is necessary for an accurate prediction of barrel life and for economically determining the effectiveness of wear reducing additives and/or coatings. Accurate round by round measurements throughout the barrel length would also be helpful in validation of analytical models for heat transfer and wear. Micrometers have been used to obtain approximate round by round measurements for large caliber weapons. However, these methods are of limited use when applied to smaller caliber weapons such as the twenty millimeter cannon. In addition, wear nonuniformities (circumferential variations, etc.) are difficult, if not impossible, to obtain using this technique. Two new approaches, each using laser optical techniques, may provide the means for accurate gun barrel erosion measurement, laser contour generation and holographic interferometry.

Laser contour generation consists of two-beam interference to reconstruct topographical contours of the subject surface. Holographic interferometry of circular cylinders to determine surface defects has been reported by Ennos [1,2]. In conventional interferometric determination of two "similar" objects, Ennos has pointed out that if the "misfit" is greater than about 1/4 wavelength (about six microinches for the .633 micron laser used in this study) then the interference patterns would be lost in noise. Thus, in order to

compare cylinder bores which had machine finishes, a less sensitive interferometer was devised. By using strongly oblique illumination and viewing directions, reflection becomes more specular but shortens the view and alters the sensitivity of measurement. The sensitivity is reduced by a factor of the cosine of the angle of incidence to the object surface. In his experiments with a cylinder length to diameter ratio of about 2.4, an angle of incidence of 83 degrees was used. This resulted in a "scaling factor" of eight which gave approximately one fringe per 100 micro-inches with an accuracy of about ± 10 micro inches. Even with oblique angles, machining differences between the two cylinders required additional special procedures such as a special lens-filter arrangement in order to eliminate scattered light.

The application of Ennos' technique to measurement of gun barrel wear requires some additional special considerations. A gun barrel has rifling which destroys the axial symmetry of the bore. Ennos indicates that without axial symmetry, illumination and spatial filtering are considerably more difficult. The length/diameter ratio of a twenty millimeter cannon is nearly two orders of a magnitude larger than the length/diameter ratio used by Ennos. To view four inches of barrel length by Ennos' technique would require an angle of incidence of 89.72 degrees which would yield a sensitivity of about one fringe per 2300 microinches. Morris [3] has

presented experimental data for a 5"/54 gun which shows that wear is of the order of 10 to 200 microinches per round, based on 1500 rounds fired. Using a mean value of 100 microinches per round wear, the 2300 microinches holographic sensitivity would require at least twenty three rounds to produce any fringe pattern. Once this fringe pattern had been established it would be possible (using Ennos' premise of estimating fringe spacing to one tenth of a fringe) to see surface wear of ± 240 micro inches or about two rounds of ammunition.

In addition to the holographic arrangement considerations, several physical problems seemed evident. A gun barrel is much longer and heavier than a seven inch cylinder and would require a large optical bench for accurate replacement. When the gun was fired there could be residue in the barrel which would cause unwanted interference patterns. During firing, the gun barrel would be placed under large stress to hold it in place and this could cause deformation that could be interpreted as wear. In his experiments, Ennos did not consider the effect of a long interval between the initial exposure and cylinder replacement. This time consideration is important for the gun barrel application.

With the aforementioned problems considered it was decided that Ennos' method might be applied to gun barrel erosion. Three cylinders with a length/diameter ratio similar to Ennos' cylinder were constructed. The cylinders were each fitted with an epoxy lining which approximated gun

barrel rifling in order to simulate the unsymmetrical gun barrel bore. The optical arrangement required for these large cylinders and the twenty millimeter cannon was similar. These optics were designed and an optical bench arrangement obtained. An important consideration was how much surface material could be removed without destroying real time interferometry and an arrangement to examine this problem was devised. This arrangement was also to be used in determining the effects of long time intervals between cylinder removal and replacement. It was felt that by careful realignment and precise optical design the techniques developed by Ennos could be used to measure gun barrel erosion extremely accurately.

II. THEORETICAL ANALYSIS

A. INTRODUCTION TO HOLOGRAPHY

In the late 1940's, an English scientist named Dennis Gabor invented a method of wavefront reconstruction which he called holography from the Greek word "holos" meaning whole. However, it was not until the advent of the laser in the early sixties that a truly coherent source of light was available. The availability of a coherent light source led to a series of experiments by Leith and Upatnieks at the University of Michigan Institute of Science and Technology which produced the basic methodology used in holography today.

Holography is the combining of two coherent light beams on an emulsion covered plate as seen in Figure 1. The plate is then developed and the object reconstructed by illumination of the plate with a coherent light source. When this illuminating source reaches the plate it forms a complex diffraction grating consisting of two first order waves which are the refractions of the original object beam and a zero order beam that is transmitted illumination (Figure 2). This refraction of the illumination wave reproduces the scene which was the holographic subject.

If the path length of the object beam and the reference beam are within the temporal coherence length of the laser, it is possible to create a hologram. If each point on the

object is assumed to be a point source spherical radiator, one can mathematically represent the hologram as a combination of any two general waves (Smith [5]).

$$R = R_o \, e^{i\phi_R}$$

$$O = O_o \, e^{i\phi_o}$$

where O is the object wave and R is the reference wave. This is possible because the photographic emulsion sees only the time averaged intensity over many periods of the wave so one need not be concerned with the time dependence of the wave. These two waves, reference and object, meet at the photographic emulsion and their complex amplitudes are additive on the plate.

$$H = O_o \, e^{i\phi_o} + R_o \, e^{i\phi_R}$$

The intensity recorded on the plate is given by:

$$I = H^2 = (O_o e^{i\phi_o} + R_o e^{i\phi_R})(O_o e^{i\phi_o} + R_o e^{i\phi_R})^*$$

where * represents the complex conjugate. The transmittance of the plate is some constant transmittance times the recorded transmittance:

$$t = \beta(O_o^2 + R_o^2 + O_oR_oe^{i(\phi_o - \phi_R)} + O_oR_oe^{-i(\phi_o - \phi_R)})$$

In the reconsturction process, the plate is reilluminated by some wave:

$$C = C_o\, e^{i\phi_c}$$

The wave transmitted by the hologram then takes the form:

$$\psi = C \cdot t = \beta(C_oO_o^2e^{i\phi_c} + C_oR_o^2e^{i\phi_c} + C_oO_oR_oe^{i(\phi_c + \phi_o - \phi_R)} + C_oO_oR_oe^{i(\phi_c - \phi_o + \phi_R)}) \tag{1}$$

which is the basic equation for holography in very general form. The third and fourth terms are the interference terms which form the virtual and real images respectively. When the illuminating wave is identical to the reference wave, it is apparent from the third term that the virtual image will appear exactly at the original position of the object. The real image derived from the fourth term is located at a point angularly displaced from the reference beam as shown in Figure 3.

It is important to locate the real and virtual images in space and to consider reconstruction by waves other than the reference wave. This can be done by considering terms

three and four in the basic equation of holography and interpreting the phase interference of these terms. In Figure 4, we represent the object as a single point source and the reference as an expanding wave. By doing this, we may represent

$$O_o e^{i\phi_o} = A \frac{e^{iK\tilde{r}}}{\tilde{r}} , \qquad \phi_o = K\tilde{r}$$

$$R_o e^{i\phi_r} = B \frac{e^{iK\tilde{s}}}{\tilde{s}} , \qquad \phi_r = K\tilde{s}$$

where A and B are the initial amplitudes and may be considered to be constant over the whole hologram. The $\tilde{r}$ is the distance between r and r_o and may be expressed in terms of the coordinate system shown in Figure 4.

$$(r-r_o) = [(x-x_o)^2 + (y-y_o)^2 + z_o^2]^{\frac{1}{2}} - (x_o^2 + y_o^2 + z_o^2)^{\frac{1}{2}}$$

This expression may be related to the phase to obtain an expression for ϕ_o. In the same manner, ϕ_c and ϕ_R can be computed in x, y, z coordinates. By using a first order power series approximation for the square roots, one can obtain an expression for each phase of the form:

$$\phi_o = \frac{2\pi}{\lambda}[\frac{1}{2z}(x^2 + y^2 - 2xx_o - 2yy_o) + \ldots]$$

When one examines the phase relationship given in term three of Equation (1), one may obtain the relative phase in coordinates of Figure 4.

$$\phi_o - \phi_R + \phi_c = \frac{\pi}{\lambda}[(x^2+y^2)(\frac{1}{z_o} - \frac{1}{z_R} + \frac{1}{z_c}) - 2x(\frac{x_o}{z_o} - \frac{x_R}{z_R} + \frac{x_c}{z_c})$$
$$- 2y(\frac{y_o}{z_o} - \frac{y_R}{z_R} + \frac{y_c}{z_c})]$$

Following the development of Smith [5], it is possible to obtain a general term for the first order reconstruction wave:

$$\Phi = \frac{\pi}{\lambda}\left(\frac{x^2 + y^2 - 2xX - 2yY}{Z}\right) \qquad (2)$$

where Z is the radius of the spherically radiating point and X and Y are the coordinates of the image. Equation (2) is a general equation, but can be specialized to locate either the virtual or real image depending on what relationships are used for X, Y, and Z. For the virtual image, the relationships are:

$$Z_v = \frac{z_o z_R z_c}{z_R z_c - z_o z_c + z_o z_R}$$

$$X_v = \frac{x_o z_R z_c - x_R z_o z_c + x_c z_o z_R}{z_R z_c - z_o z_c + z_o z_R}$$

$$Y_v = \frac{y_o z_R z_c - y_R z_o z_c + y_c z_o z_R}{z_R z_c - z_o z_c + z_o z_R}$$

As mentioned before, if the illuminating wave is the reference wave where $z_R = z_c$, $x_R = x_c$, $y_R = y_c$ then these reduce to $Z_v = z_o$, $X_v = x_o$, $Y_v = y_o$ which makes the virtual image appear exactly where the original object was located. This fact will be an important consideration when addressing the problem of fringe location using real time interferometry.

The real image location is described by Equation (2), where X, Y, Z are of the form:

$$X_R = \frac{x_c z_o z_R - x_o z_c z_R + x_R z_c z_o}{z_o z_R - z_c z_R + z_c z_o}$$

$$Y_R = \frac{y_c z_o z_R - y_o z_c z_R + y_R z_c z_o}{z_o z_R - z_c z_R + z_c z_o}$$

$$Z_R = \frac{z_o z_R z_c}{z_o z_R - z_c z_R + z_c z_o}$$

When the illuminating wave is the reference wave, this set of coordinates provides a real image location a distance z_o behind the plate, but offset by the first order diffraction grating as shown in Figure 3.

The above development [Smith - Chapter 3] does not address the problem of reconstruction by use of some wave length other than that used to record the hologram. The development in Collier [6] considers this and introduces a ratio (μ) of the reconstructing wave length to the forming wave length. This ratio becomes a part of Equation (2) and can produce

location and magnification effects on the resulting images. This is an important consideration in pulsed holography, but not in the experiments done in conjunction with this study, as all reconstruction was done with the original CW reference beam.

B. HOLOGRAPHIC INTERFEROMETRY

When a hologram storing more than one wave is illuminated with coherent light, the reconstructed waves can interfere with one another [6]. This is very similar to ordinary interferometry but the unique ability of a hologram to store the interference gives more flexibility in application. When a hologram is double exposed, the film will record two diffraction patterns and these will interfere with each other upon reconstruction. This interference will be very evident when the object receives a small displacement between exposures. This type of holographic interferometry is called time-lapse and provides a permanent record of the displacement in its interference fringes.

A second type of holographic interferometry is called real time or live fringe. In this process, the hologram is replaced as closely as possible to its original position and interference patterns can be formed by either object or hologram displacement. These interference patterns can be observed to change with time and hence the name real-time. While real-time holographic interferometry has many applications, the

problem of exact replacement of the developed hologram can be extremely bothersome. This task can be made somewhat easier by developing the plate in place, but this requires a special type of hologram holder.

Interpretation of fringes obtained from a displacement (δ) between exposures or a real-time displacement is the same for each case. Referring to Figure 5 and following the development of Floyd and Collins [7] the phase along each path is given by:

$$\delta_1 = K_2 \cdot r_2 + K_2 \cdot (R - r_1)$$

$$\delta_2 = K_3 \cdot r_3 + K_4 \cdot (R - r_3).$$

Assuming:

$$K_3 = K_1 + \Delta K_1$$

$$K_4 = K_2 + \Delta K_2$$

the phase difference is given by:

$$\delta = \delta_1 - \delta_2$$

$$= (K_3 - K_2) \cdot (r_2 - r_3) - \Delta K_2 \cdot r_3 - \Delta K_2 - (R - r_3).$$

The arbitrary displacement (d) is the difference between r_3 and r_1, and ΔK_1 and ΔK_2 are perpendicular to r_3 and $(R - r_3)$. This gives:

$$\delta = (K_1 - K_2) \cdot d$$

which is the general expression for phase difference. This δ can be applied to specific cases in order to provide fringe spacing expressions for various displacements of the subject.

III. METHOD OF INVESTIGATION

Experiments were first conducted to familiarize the investigator with holographic interferometry by using both the live and frozen fringe techniques. These consisted of the repetition of the Collins and Floyd [7] experiments using the double exposure frozen fringe technique to measure object rotation and translation. These tests were then repeated using a live fringe method. A series of experiments were then conducted using flat plates to determine how much surface removal (wear) could be measured and to study the practical aspects of long intervals between exposure and interpretation of the real time fringe pattern.

Three cylinders were designed to determine the applicability of the Ennos technique (Figure 6) to the special problems presented by gun barrel rifling. Each succeeding cylinder more closely approximated a gun barrel. The first was a smooth cylinder, the second had straight grooves, and the third had grooves with a twist of five degrees per inch. This third cylinder would closely approximate a gun barrel. The optics required for actual use of the technique in the 20mm barrel were also designed. Results of the flat plate experiments precluded proceeding with the cylinder applications.

IV. EXPERIMENTAL APPARATUS

The holographic arrangement used is shown in Figure 7. Different objects were used as the holographic object for each series of experiments. The monochromatic source of coherent light used was a fifteen milliwatt Spectro-Physics helium neon laser with a 6328 Angstrom wave length. The laser was equipped with a six micron spatial filter and collimator arrangement which provided a very clean light source. During the repetition of the Collins and Floyd experiments, the subject was a metal block with numerals attached to it. The numbers made the images from even marginal quality holograms readily visible. This block was mounted on an X-Y translating table for the lateral translation portion of the experiments and on a rotating table for the rotation portion. The X-Y translating table was also used for some of the later surface structure experiments, but it did not have the precision required for use in real time holographic interferometry.

The concept of the dual hologram holder was developed by Havner and the one pictured in Figure 8 was built at the Naval Postgraduate School by Collins. The dual hologram holder has six degrees of freedom which are controlled by six Tropel piezoelectric micrometers powered by a high quality voltage source. These micrometers are accurate to

a fraction of a micron and are able to provide the control required for real-time interferometry. Each of these micrometers was calibrated using a Bendix magnetic field influence device and a digital voltometer. The calibration curves are non-linear and an example is shown in Figure 9.

For the type of real-time holographic interferometry done in this investigation, it was found that better results were obtained if the dual hologram was used to translate the holographic object rather than the hologram itself. The dual hologram holder became an integral part of the holographic arrangement and its relative position is shown in Figure 10. During exposure, and after development, the hologram film plates were held in a distilled water environment. This provided a uniform medium for the interference to take place. The use of a wet holder eliminates any variation in the index of refraction in the vicinity of the hologram plate. In addition, the particular holder used in these experiments had two degrees of freedom controlled by mechanical micrometers. These two degrees of freedom were redundant to the dual hologram holder but at times proved useful in making large adjustments.

When conducting experiments on the effects of change in surface microstructure, it became necessary to build the device shown in Figure 11. This device enabled a brass plug to be translated forward and backward minute amounts by use of one of the aforementioned piezoelectric micrometers.

A teflon ring was installed to prevent any rotation and scribes were put on the surface to detect any rotation. The rotations that were involved were of such a small nature that the surface scribes were aligned and monitored by use of a four power magnifying glass.

The apparatus that was to be used in the holographic interferometry of grooved circular cylinders was designed and constructed and is reported in Appendix A. However, none of this equipment was used in the current investigation.

V. EXPERIMENTAL PROCEDURES

A. LABORATORY PROCEDURES

The first series of experiments to reproduce the Collins and Floyd results used the set up shown in Figure 12 with fair success. These experiments were later repeated using the dual hologram holder arrangement shown in Figure 8 with much better success and resulted in the curve shown in Figure 13 and the photographs in Figure 14. To obtain correlation between real time and time lapse (double exposed) interferometry, the lateral translations in X and Y were repeated using real time interferometry. The real time fringes gave good agreement with the time lapse fringes as can be seen from the comparative plot in Figure 15. The photographs of the real time fringes in Figure 16 look very similar to those of the lapsed time. In actuality, the object has been removed in the lapse time photographs and the image is projected onto a dark background. In the real time photographs the fringe pattern is caused by the surface of the object interfering with the singly exposed hologram. To duplicate the lateral translation experiments with real time interferometry was not difficult once the hologram and object were replaced in their original relative positions. However, realignment presented unexpected difficulty.

In an attempt to determine the amount of surface removal that could be measured by real time interferometry a series

of experiments were conducted in which nitric acid was used to etch a copper plate. This combination of acid and metal was selected because of afinity of nitric acid for the copper ion. In these experiments the arrangement used was that shown in Figure 17 with a copper plate mounted on the X-Y translator as the holographic object. A hologram was taken and, when replaced after development, it formed a series of real time fringes with the surface of the plate. There was no intentional movement of the object between exposure and the replacement of the holographic plate. The fringe pattern which resulted was due to two effects. The first of these was the shrinkage of the photographic emulsion, but this effect is minimized if one chooses the angles between the reference and object beams properly. The second effect was the inability to replace the developed hologram in precisely the same position where it was exposed. The X-Y translator gave some degree of fringe control as did the two degrees of freedom of the hologram plate holder. Using these adjustments, horizontal live fringes were obtained. However, these fringes could be due to pure rotation or pure vertical translation depending upon where they were localized. These horizontal fringes were to be used as the reference from which any surface erosion due to the nitric acid would be measured. However, when nitric acid was allowed to etch the surface of the copper plates, the horizontal fringes

became discontinuous on that portion of the plate where the acid had been. Several acid concentrations were tried with the same result. It was felt that perhaps the marked change in color which took place when the copper was etched could have caused the discontinuity, since the color change indicated some change in microstructure. The tendency of copper to become very shiny when etched and the extreme difficulty in calculating how much surface had been removed by the nitric acid etching caused this approach to be discarded.

The need for precise fringe control led to the use of the dual hologram holder as a device for translating the holographic object. A stainless steel plate was mounted in the dual hologram holder and was used as the holographic object for a series of experiments. This arrangement provided much better fringe control and allowed very precise relative repositioning of the hologram plate. Several grooves varying between one and five thousandths of an inch in depth were milled vertically along the edge of the stainless steel plate to provide a reference for any surface displacement measurement. After an acceptable set of reference fringes were obtained on the stainless steel plate, photographs were taken. The plate was removed and immediately replaced without loss of the live fringes. Therefore, for short time intervals, use of the dual hologram holder and simple positioning procedures allowed successful replacement

of the object. The stainless steel plate was then removed and several new grooves were milled onto the surface. It was hoped that comparison of the reference grooves to the newly milled grooves would provide an indication of measurable surface erosion. However, once the plate was removed and milled it was never possible to replace it close enough to its original position to determine the relationship between the new grooves and the reference ones. This indicated that, even with the less sensitive requirements of the gun barrel, repositioning after relatively long time intervals may be quite difficult. Since the above techniques did not allow wear to be measured, another device was devised which would not require removal of the object (see Figure 11). This device allowed a one half inch brass plug to be translated along an axis perpendicular to the hologram plate. Thus a portion of the original surface was "worn" but the surface structure was maintained identical. The use of one of the Tropel piezoelectric micrometers in this "Z axis" translator provided excellent control over the movement of the brass plug. During this series of experiments a collimator was used in the object beam. The collimator was placed in the object beam in order to provide plane wave illumination of the object so that any translation in the "Z" direction would produce fringes which were localized at infinity [8]. By using all six degrees of freedom of the dual hologram holder to reposition, it was possible to obtain a real

time infinite fringe arrangement. (i.e. when there was but one or two heavy black fringes in the field of view as shown in Figure 18). This condition occurs when the relative position of the object and hologram are within one wave length of the original relative object and hologram position. It was from this infinite fringe position that the first Z translation experiments were conducted. The results of this experiment are shown in Figure 19.

In order to examine the effect of any extraneous translation, the same experiment was run with a known lateral translation. This provided the results shown in Figure 20. It was considered very important to know if there was any rotation of the brass plug about the Z axis, and if there was, what would the effect be on the fringes which appeared when the plug was translated.

For this reason pure rotation about the Z axis was investigated by the lapse time technique. The investigation of rotation about the Z axis did not prove difficult as this was one of the motions provided by the dual hologram holder.

While the Z translator provided insight into how much displacement could be measured by real time interferometry it did not address the problem of changes in surface microstructures. One approach which was used was the removal of a thin layer of paint from a plate mounted in the dual hologram holder. First the plate thickness was measured and then a small area was sprayed with two ten thousandths of an inch layer of black paint (which was practically transparent).

This plate was mounted and a hologram was taken. After hologram replacement, the paint was carefully removed from the subject by using acetone. It was very important not to cause any displacement of the plate while removing the paint. The removal of the paint while in an infinite fringe condition did not produce any usable data so the experiment was conducted again. This time a known lateral translation was introduced after the infinite fringe condition had been obtained. This resulted in the effects shown in Figure 21 (i.e. fringe gaps across where the paint was located).

The results of the experiment which used the thin paint layer were of limited use because the distinct differences in the microstructure of materials. It was important to determine what effect the erosion of a surface would have on the quality of any real time interferometry. The dual hologram holder was very easily moved and this presented considerable difficulty when trying to remove surface structure of a material that was being held in it. Any movement would cause a change in the interference pattern and negate any information which was contained in the pattern. Due to the aforementioned sensitiviy it was decided to use some material other than metal for the experiment. A piece of masonite fiberboard was selected and cut to fit in the dual hologram holder. The masonite was selected because it was strong enough not to deform when measured with a micrometer, yet it could have its surface structure easily changed with an emery cloth. The reflectivity of the masonite was poor so the

the results obtained could not be photographed, but the experiment did demonstrate the effect of surface structure change on real time interferometry.

B. PHOTOGRAPHIC TECHNIQUES

Holograms were recorded on two types of Agfa-Gaevert hologram plates, 8E75 and 10E75. The latter requires less exposure time and was used exclusively on all real-time holographic interferometry. An abbreviated development process was used:

(1) Three to five minutes in Kodak D-19 developer
(2) Thirty seconds in diluted acetic acid stop bath
(3) One minute in standard rapid fixer
(4) Thirty seconds flowing water bath.

Some success was obtained using a variable development technique which used a wrattan filter, series number 3, on a dark room lamp. The hologram would be periodically viewed during development under this filtered light and placed in the stop bath when it appeared to have the proper consistency. This process is very subjective but can help to eliminate the problem of very dark holograms due to over exposure. The darkness of the hologram was of concern because real-time fringes are best veiwed and photographed through holograms which are slightly under exposed.

Photography of real-time interferometry patterns presents a problem because of the small amount of available light. Exposure times of five or more seconds were required for all films used. Due to the extreme sensitivity of the real-time

fringes, it was important to keep exposure time as short as possible. To do this, films with very high ASA ratings were used. However, a problem with film grain size was encountered when very sensitive film was used. A proper balance between sensitivity and film grain was found to exist using exposures between five and ten seconds with Kodak high speed recording film number 2475. This film and exposure produced results with enough clarity that fringe spacing could be easily measured from the finished photographs.

C. DATA REDUCTION

The technique for measuring lateral displacement is reported many places and is done by an analogy to Young's experiment which yields:

$$D = \frac{\lambda R}{X}$$

where D is fringe spacing, λ is the laser wavelength, R is the distance from the hologram plate to the object, and X is the lateral displacement. This method was applied to both the time lapse and real-time lateral displacements.

For the Z translation experiments, the fringe spacings for three different sets of motion were measured and plotted (Figure 22). The fringes were measured over a one half inch plug which, when considered with respect to the camera position, comprised a 1.2 degree field of view. The fringe spacing was converted to fringes/degree and plotted versus translation in the Z direction (Figure 23).

VI. EXPERIMENTAL RESULTS AND DISCUSSION

The holographic results from the initial experiments which were a repetition of the Collins and Floyd experiments were not of high quality due to the lack of adequate control of object movement between exposures. However, once the dual hologram holder was used to translate the object, excellent results were obtained. These results were in very good agreement with predicted values as shown in Figure 13. The photographs in Figure 14 show representative translation in the X and Y directions with the resulting time lapse fringes.

When the lateral translation experiment was done using the real-time interferometry, the results seemed to be very consistent with the lapse time technique as shown in Figure 15. There were two problems encountered when using this type of holography. The major difficult was in replacing the hologram and the holographic object in a relative position which was within a wave length or two of the laser's light. Even with the six degrees of freedom of the dual hologram holder coupled with the two redundant degrees of freedom of the wet plate holder, it was quite often an impossible task to obtain an infinite fringe pattern once the hologram had been replaced after being developed. After an infinite fringe pattern had been obtained, various displacements were introduced to produce the desired interference pattern.

This interference pattern and resulting fringe spacing was very difficult to photograph due to the extreme sensitivity of real-time holography to any vibration in the area.

When one views the series of experiments that dealt with surface microstructure as an entity, they all produce essentially the same result, but each in its own way. The acid etch experiment produced fringes which completely faded when the nitric acid was poured down the surface of the copper plate. This fringe disappearance was originally thought to result from the change in surface color when the acid removed the oxidized copper surface. In reality, the break in the real-time fringes was probably due to the minute changes which took place in the surface microstructure. The next experiments involved the removal of a stainless steel plate and replacing it after small grooves were milled into its surface. While it was never possible to replace the plate accurately enough to achieve the desired effect, the results seem quite predictable: the grooves would not have produced a shift in the fringe spacing as was hoped but rather a lack of any fringes at all on the newly milled grooves. The surface structure differences would not be as critical when using the oblique viewing angles of the Ennos technique. However, the larger object, longer time interval between exposures, and the possible deposits on the bore from the projectile may render the technique impractical.

The experiment which removed a nearly transparent two ten thousandths of an inch layer of paint from a steel plate

was the real key to what degree of surface material removal could be tolerated in holographic interferometry. The vertical fringes which were introduced by a known lateral translation disappeared across the painted circle when the paint was removed from the plate. The effect is apparent in Figure 21 where the paint is still visible in the photograph because its image is contained in the virtual image reconstruction. However, the interference fringe pattern has disappeared in the area where the paint was located. It was felt that from the masonite experiment one would be able to determine if removal of a very small amount of surface material, of the order of 10^{-5} inches, would destroy all real-time fringes. The fiberboard plate was carefully measured and a map of its thickness at various areas recorded. As mentioned before, the fiberboard did not produce good quality holograms and photography was therefore not possible. It did appear that any place where the fiberboard plate was rubbed with emery the real-time fringes disappeared. This seemed to be true even where the amount of surface material removed was of the order of 10^{-5} inches. The results obtained from these four experiments all appear to imply that surface material removal may sufficiently change the surface microstructure to make real-time interferometry in gun barrels impractical.

In contrast to the above experiments, the translating plug experiments were conducted to simulate local wear in

which the surface structure was unchanged. The results which were obtained were unusual and somewhat unexpected. The plot in Figure 22 shows that the fringe spacing versus movement curve has a 1/x shape which is in basic agreement with the results of Vienot [8]. However, there is two orders of magnitude difference between these results and Vienot's. Repeated experiments of both the live and frozen fringe techniques with Z translation of the brass plug appeared to indicate that the type of fringes shown in Figure 19 and Figure 20 are a result of an inability to duplicate the original relative positions of the hologram and the object. Vienot indicates that if the object beam is a plane wave, as it was in these experiments, there should appear highly contrasted curved fringes localized at infinity. When the lapse time technique was used, results consistent with Vienot's were obtained. When real time fringes were used with a near infinite fringe (Figure 19) or with a known lateral displacement introduced (Figure 20), the resulting fringe pattern on the translating plug was much sharper and appeared to be localized somewhere close to the surface of the plate.

When the Z translation experiment was done from the near infinite fringe starting point, all fringes appeared to have the same angle with the horizontal, approximately thirty five degrees (Figure 19). When the experiment was conducted with a known initial lateral displacement, it was not possible to obtain continuous fringes across the plug (Figure 24).

But when the plug was translated, the fringes appeared to align themselves at the same angle as the infinite fringe case (Figure 20). The data from the translation with a known displacement seems to have the general 1/x shape except at the origin where the initial set of fringes prevent the curve from approaching infinity (Figure 22). When the number of fringes per degree was plotted versus movement (Figure 23), a linear curve resulted which was again in agreement with Vienot, but still was two orders of magnitude more sensitive. The number of fringes which appear on the translating plug is directly proportional to the translation vector. No exact mathematical method for predicting fringe spacing for Z translation was developed, but it is felt that the proper specializations of the general translation equation for holography given by Stetson [9] and others would produce a method capable of such a prediction. These fringes were felt to result from pure translation in the Z direction because all movement was done by voltage inputs to the Tropel piezoelectric micrometers, and they move by crystal expansion. The lapse-time rotation experiments discussed above resulted in large fringe rotation. This fringe rotation was a function of viewing distance which was not evident in the plug translation experiments.

VII. CONCLUSIONS

A method for using real time holographic interferometry to measure gun barrel erosion was proposed and investigated. This method was based in part on the work done with smooth circular cylinders by Ennos [1,2]. A series of holographic experiments were conducted using primarily the arrangement shown in Figure 10. Using this arrangement it was determined that removal of surface material of the order of 10^{-4} inches would so alter the surface microstructure that any real time interference with that surface would be destroyed. Some evidence was found that a surface material removal of 10^{-5} inches would cause the same effect. These experiments were conducted with an angle of incidence of thirty degrees and a view angle of zero degrees. Ennos was able to measure surface displacements of 10^{-4} inches using higher angles of incidence and viewing (83 degrees for both). It is felt that this disparity in incidence angle between these experiments and the angle used by Ennos make direct comparisons between the two experiments inappropriate. It was found that when removing an object which is the subject of a real time hologram, accurate replacement is exceedingly difficult if not done within a matter of minutes. It was also found that, if stresses were applied to an object while it was out of position, accurate repositioning was impossible. This phenomena would cause significant problems in applying the developed technique to a gun barrel.

Further experiments, using the cylinders and arrangement developed here, do appear warranted. If the problems involved in interpreting the fringes caused by the simulated rifling could be overcome it would then be feasible to investigate wear by placing the diverging lens some distance down the rifle bore. This unusual placement would be necessary so that one would be able to realistically look at one or two inches of barrel length. By doing this it may be possible to determine wear with one round accuracy after firing only a dozen rounds.

While investigating the gun barrel erosion problems, data concerning real time interference while translating an object parallel to the direction of observation was acquired. If the surface microstructure of a material is not altered, a translation parallel to the direction of observation appears to be predictable and measurable from the resulting fringe spacing.

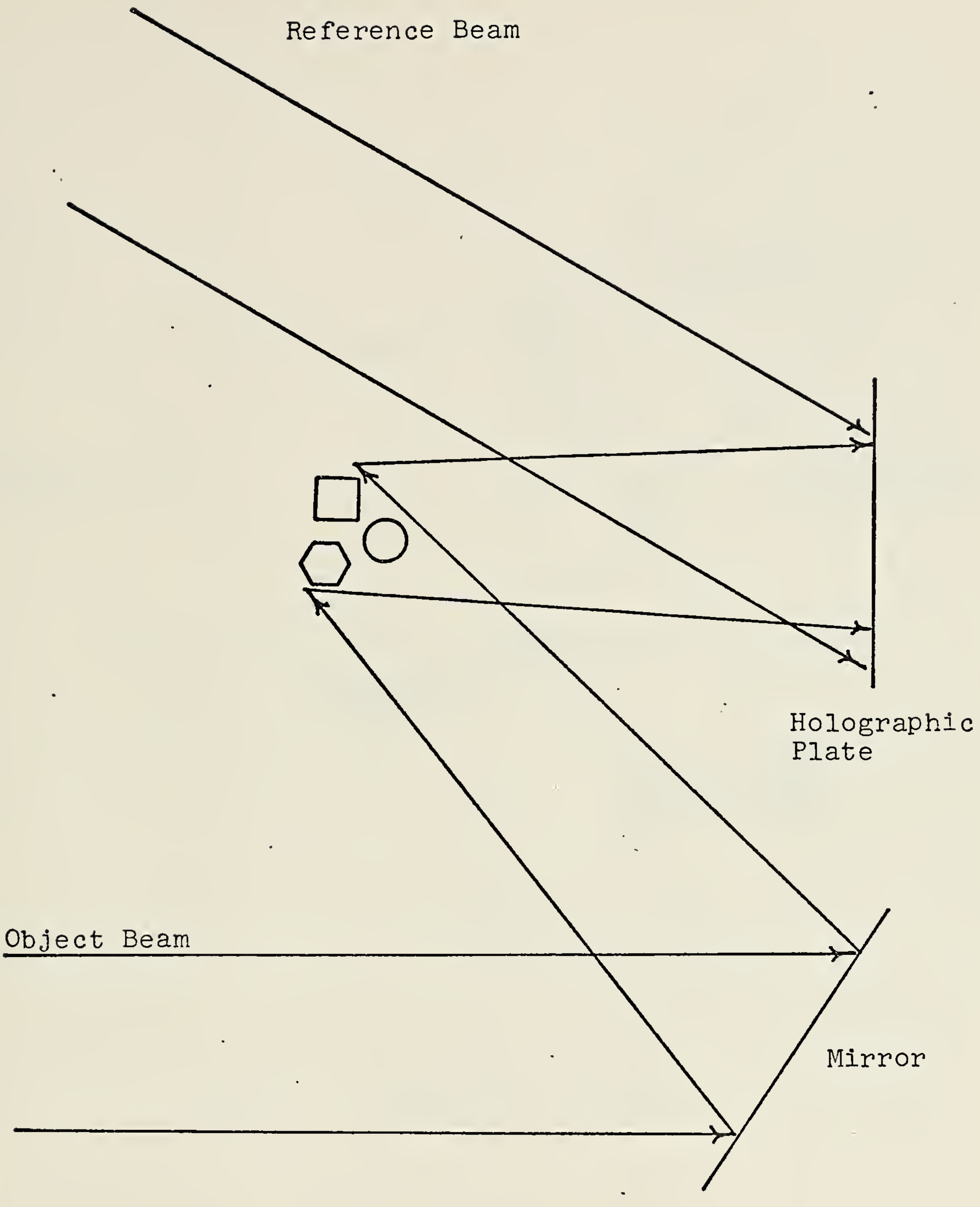


FIGURE 1. Holographic Mirror Arrangement

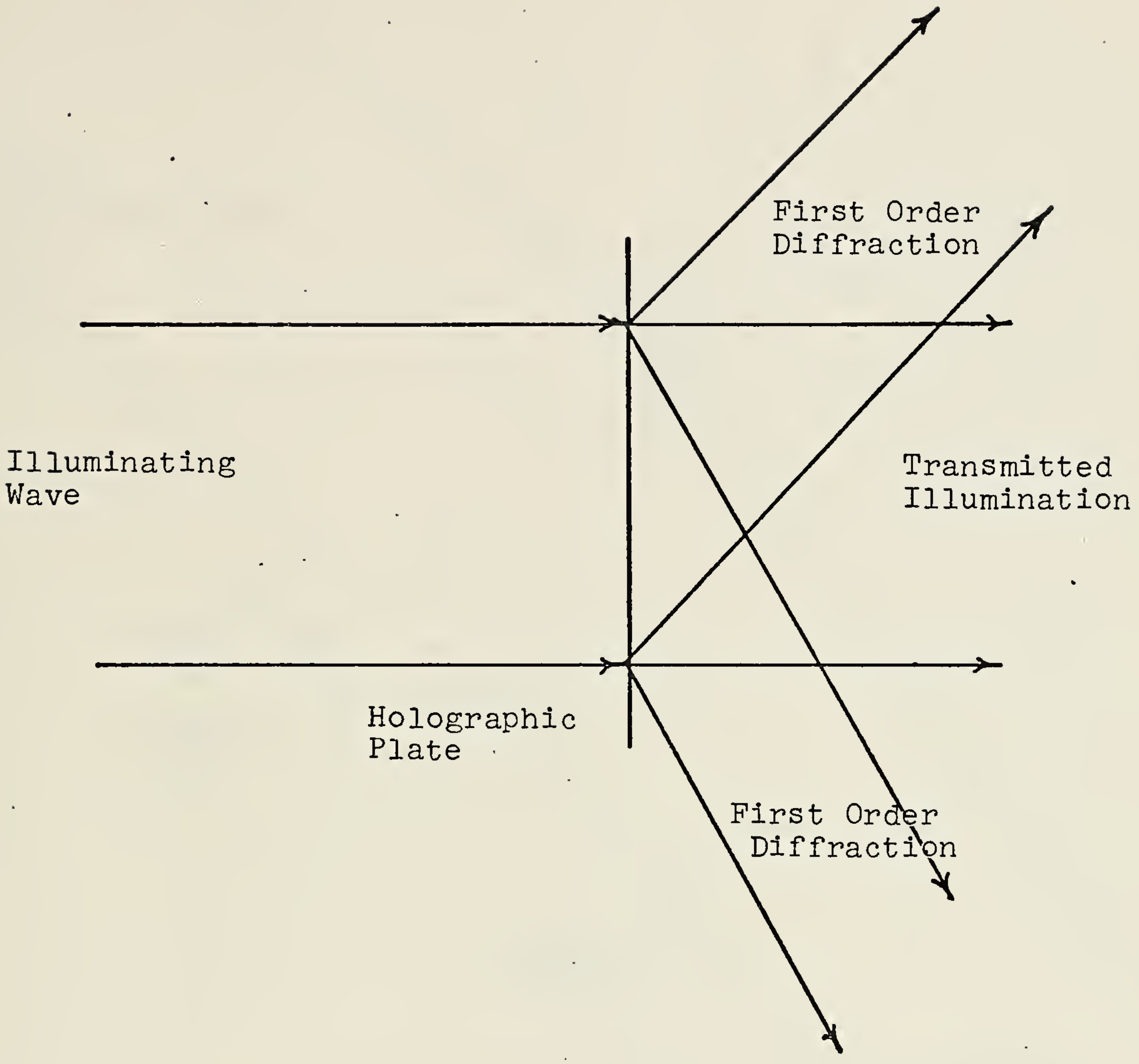


FIGURE 2. Diffraction Grating

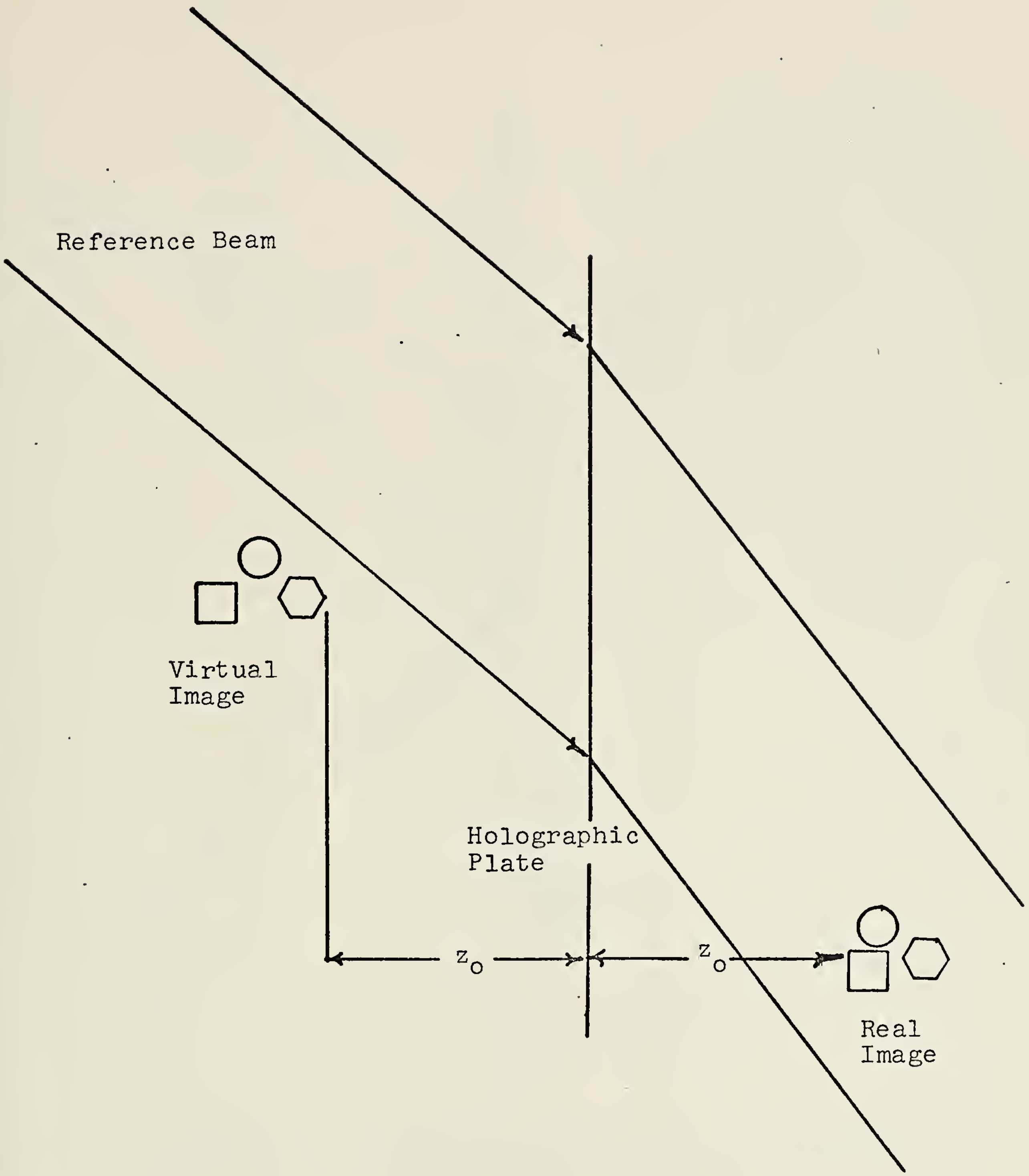


FIGURE 3. Reconstruction Images

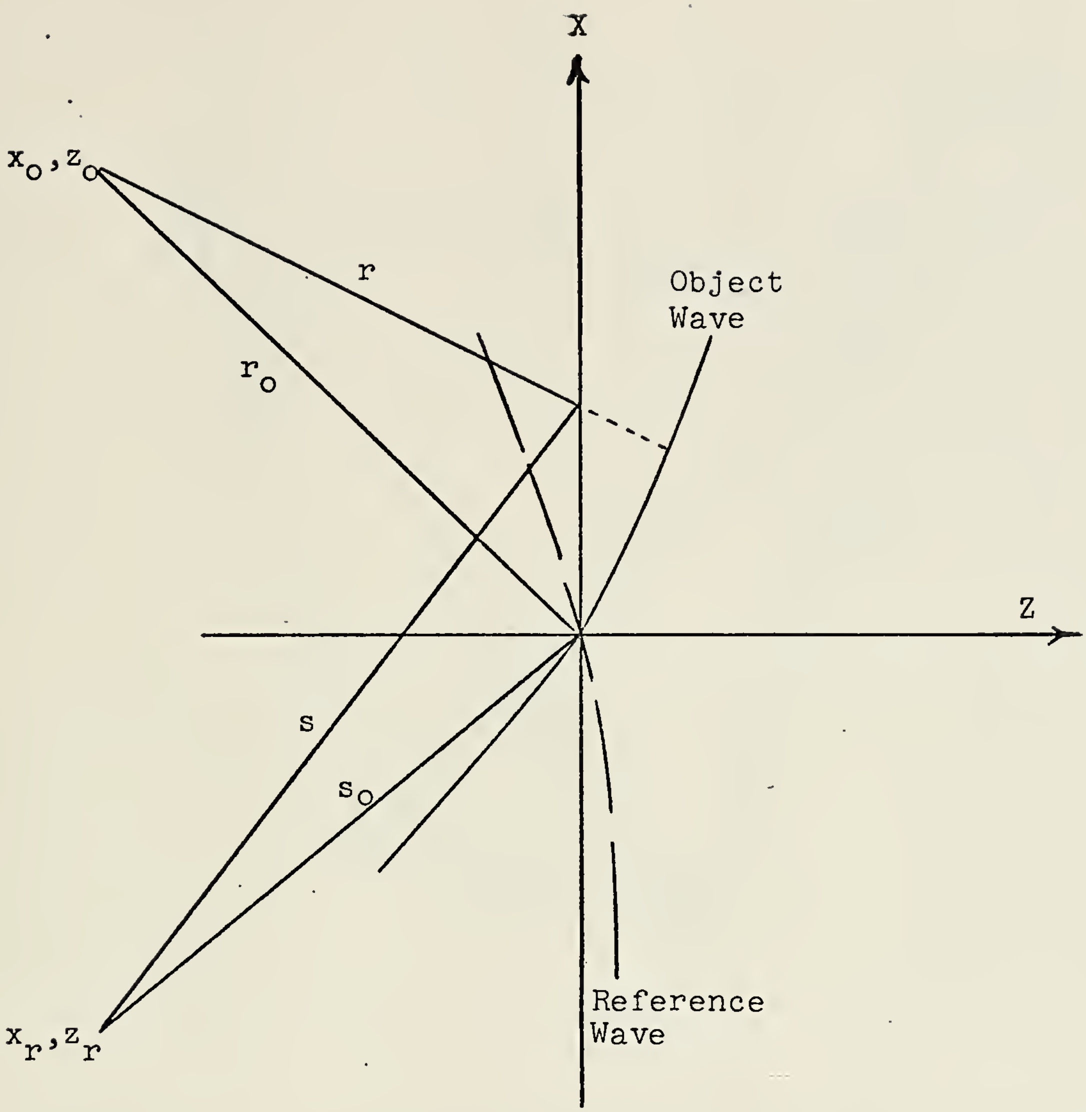


FIGURE 4. Coordinated System for Interference Pattern (Smith, Chapter 3, [5])

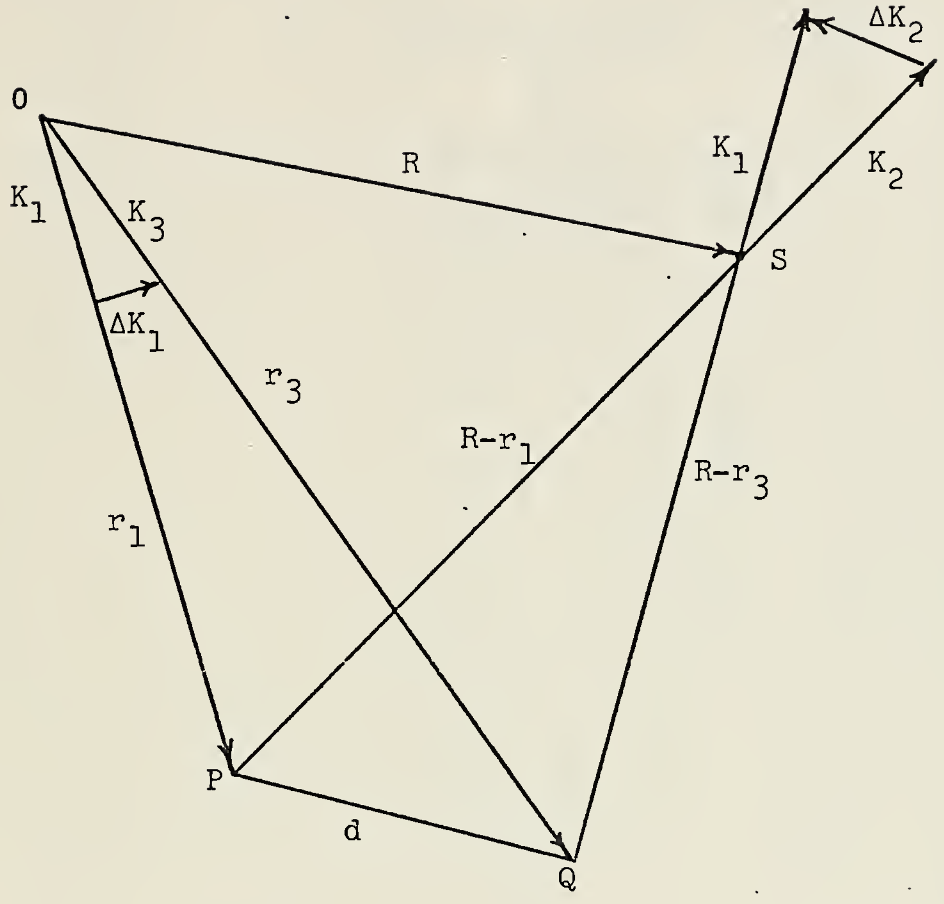


FIGURE 5. The Interference Due to a General Displacement d (Collins and Floyd [6])

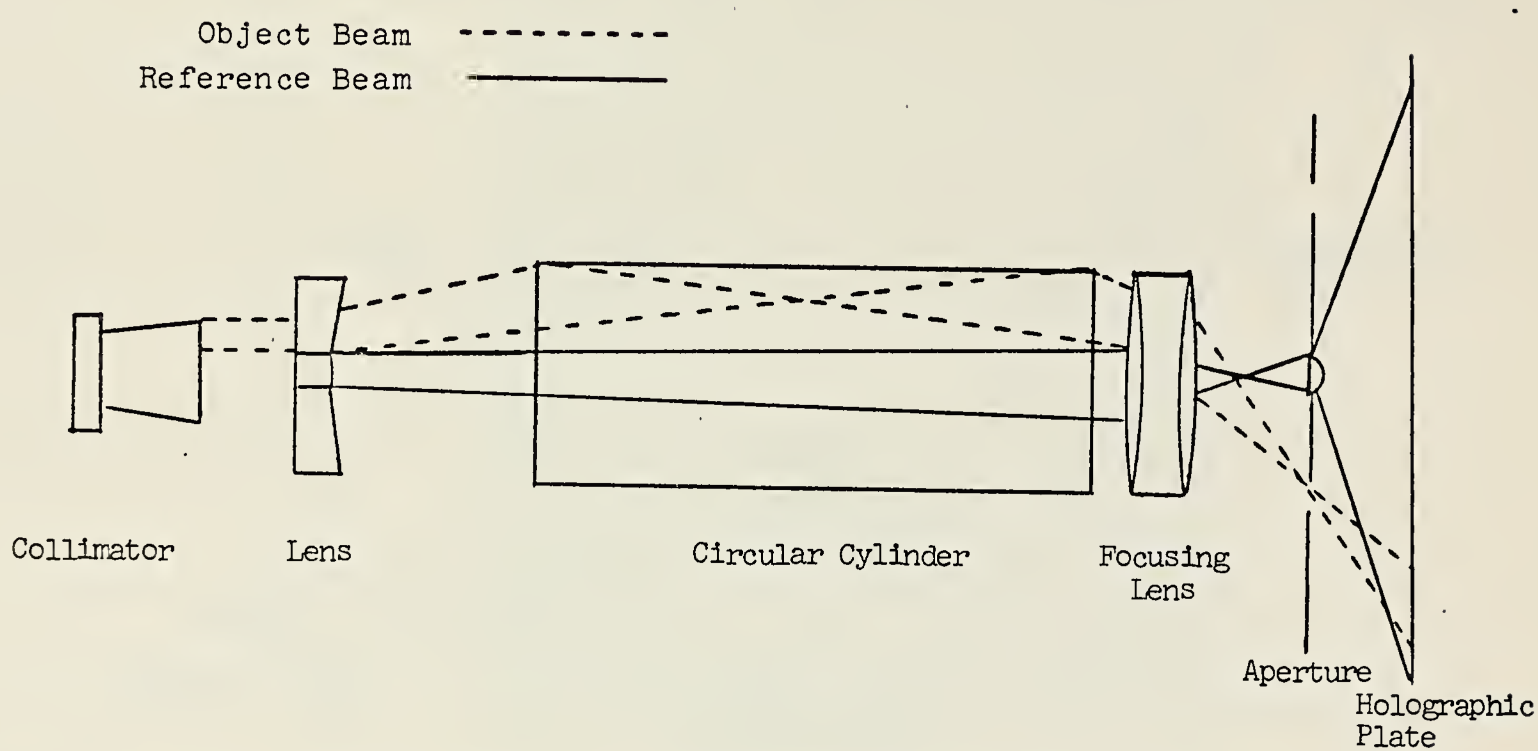


FIGURE 6. Holography Arrangement of Gun Barrel Approximating Cylinders (Ennos [2])

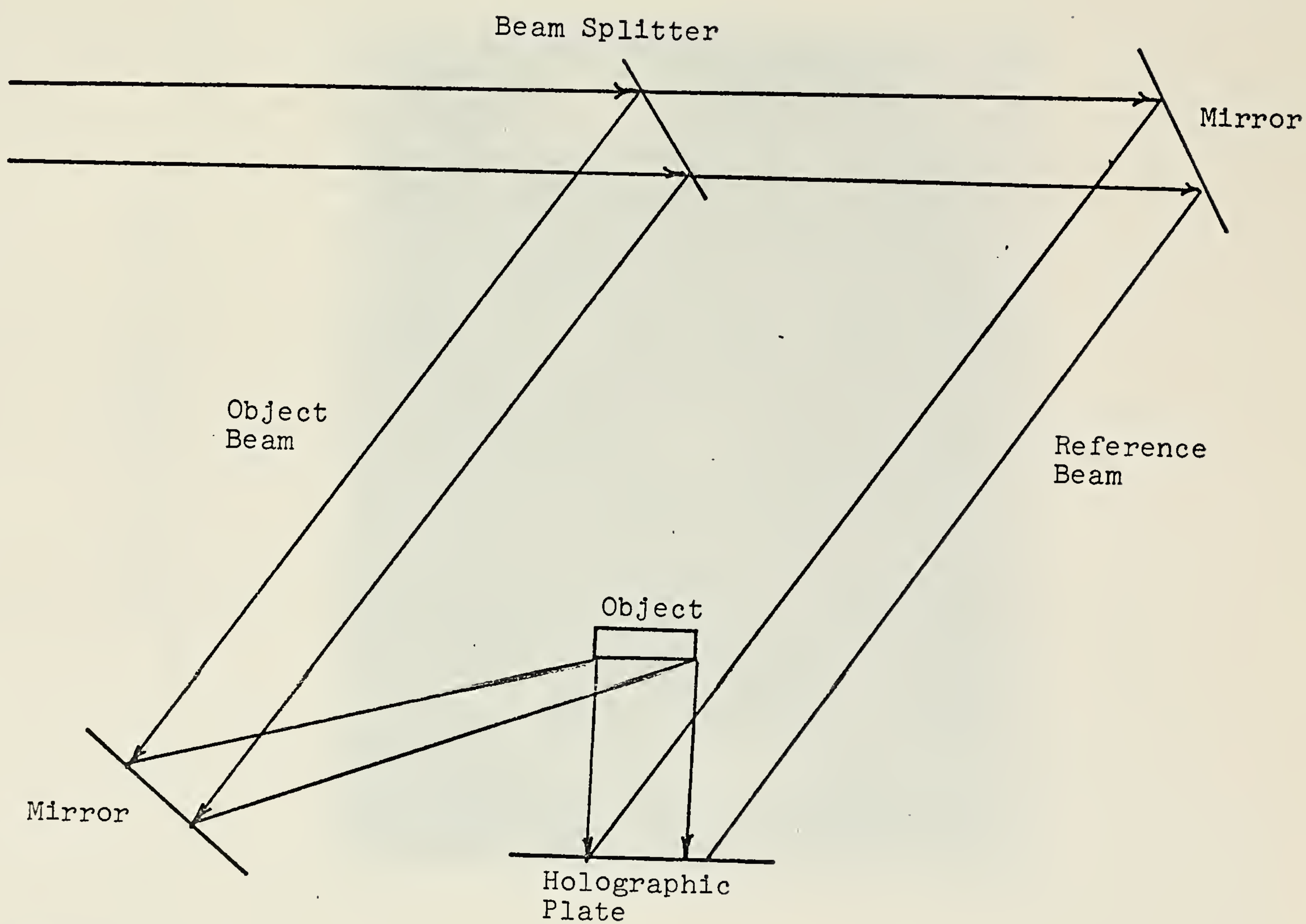


FIGURE 7. General Holographic Arrangement

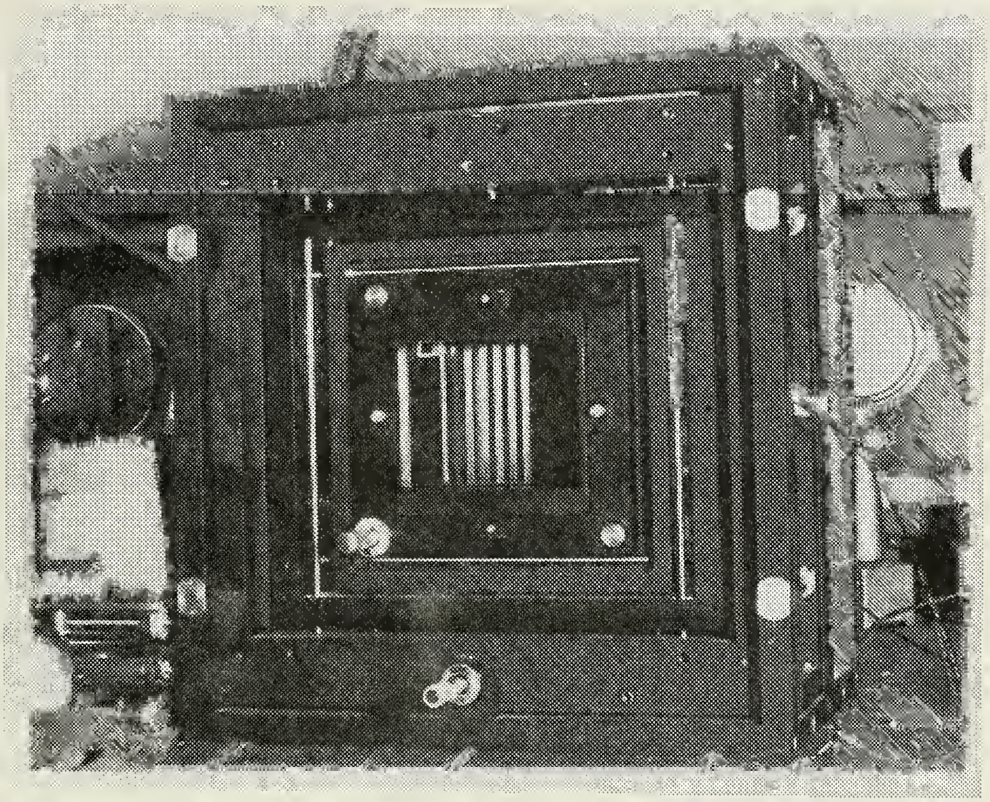


FIGURE 8. Dual Hologram Holder Constructed at Naval Postgraduate School

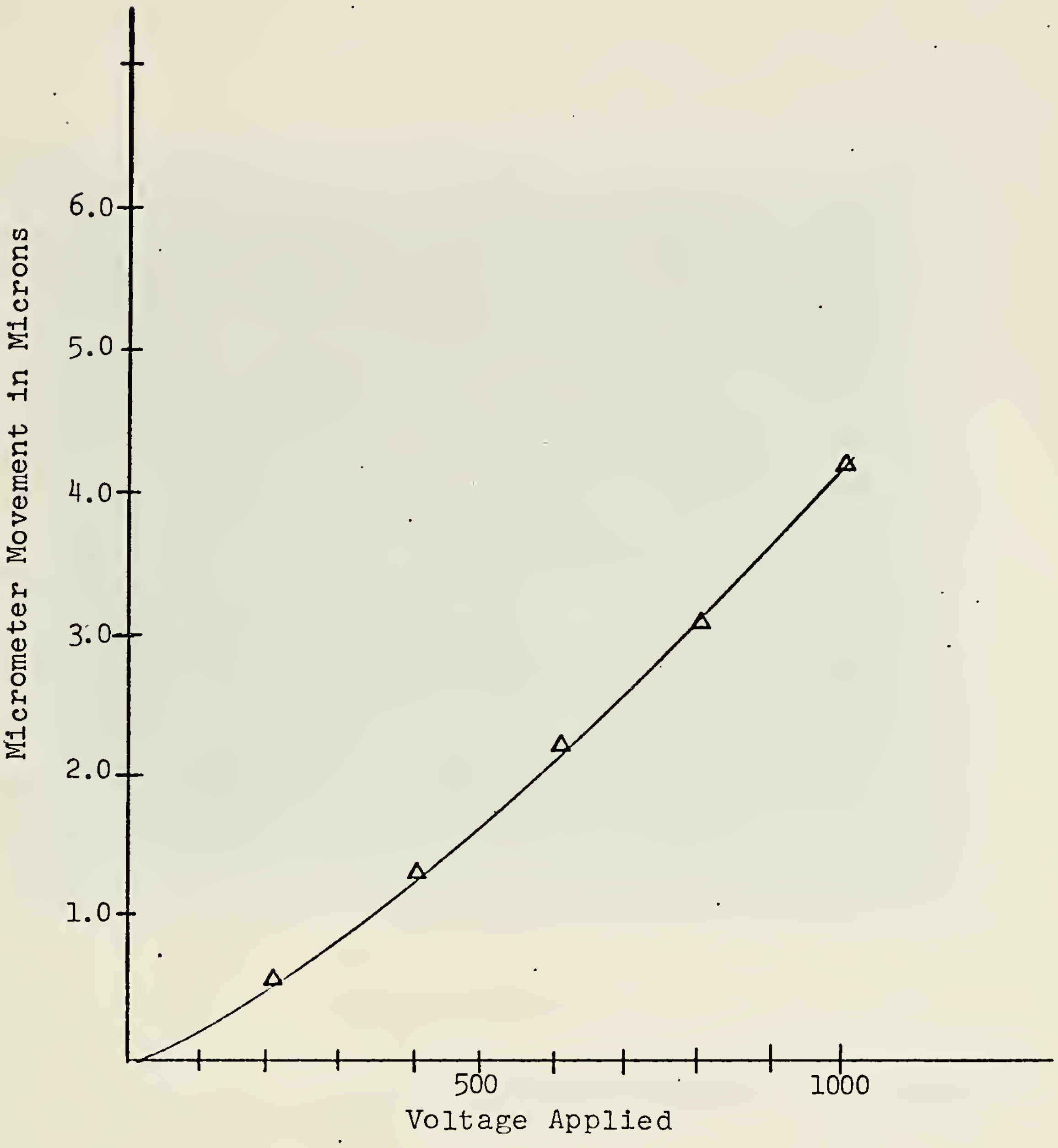


FIGURE 9. Sample Calibration Curve for a Tropel Piezoelectric Micrometer

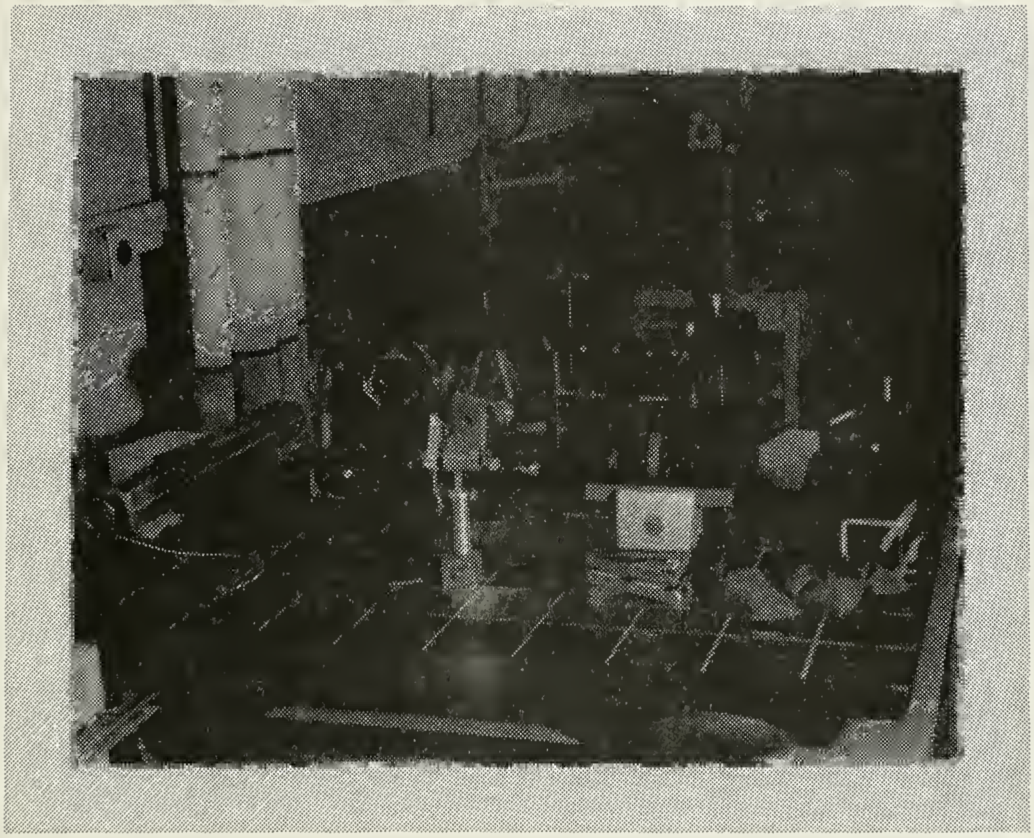


FIGURE 10. Photograph of Primary Holographic Arrangement

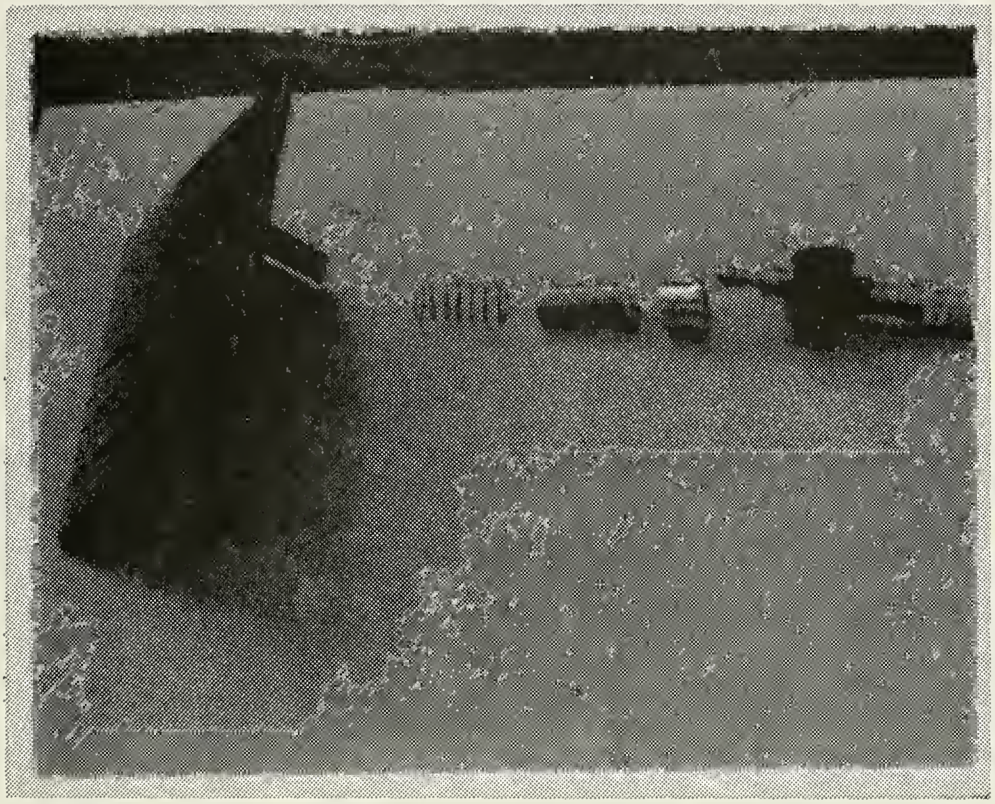


FIGURE 11. Z Translating Device

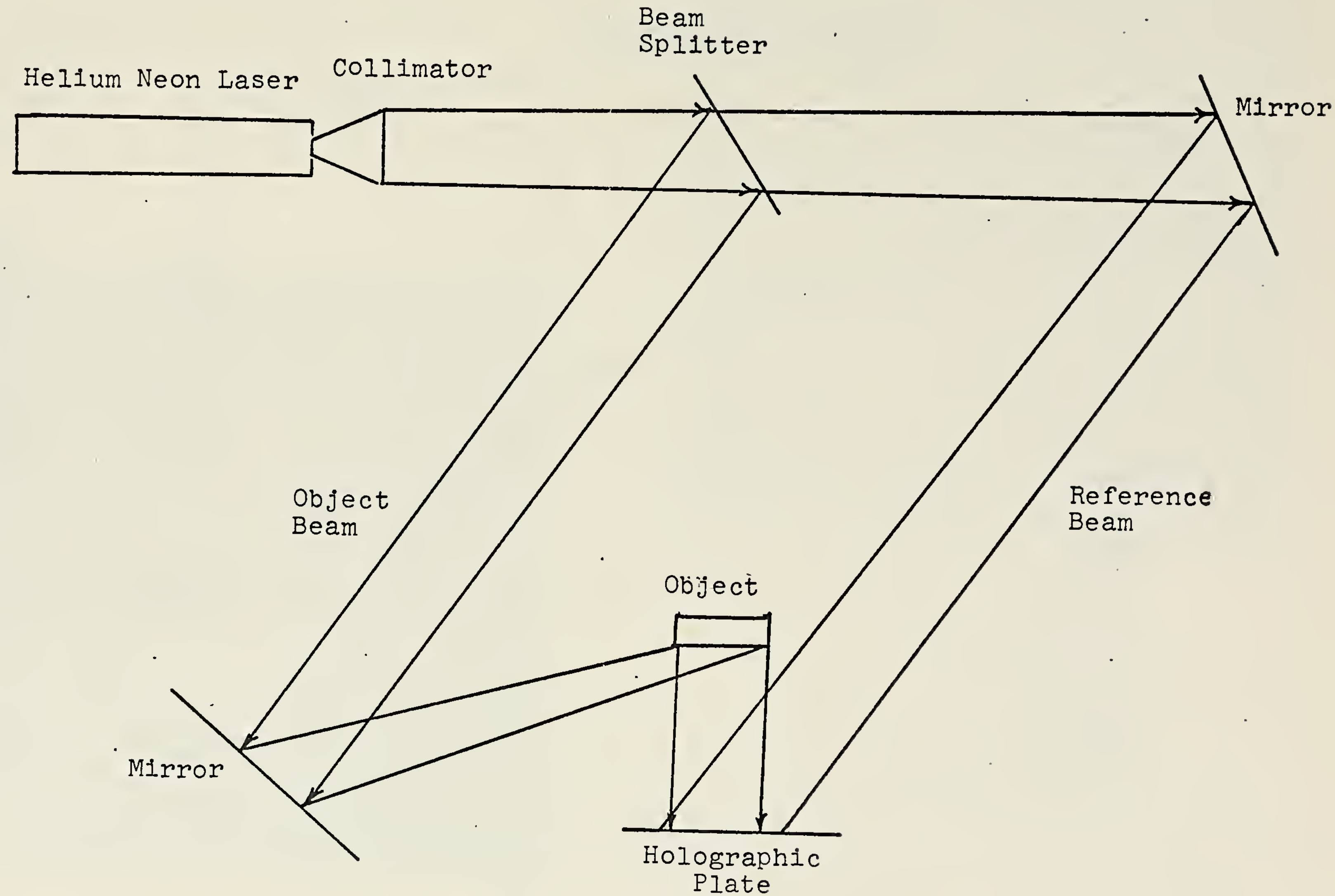


FIGURE 12. Holographic Arrangement used for Translation and Rotation

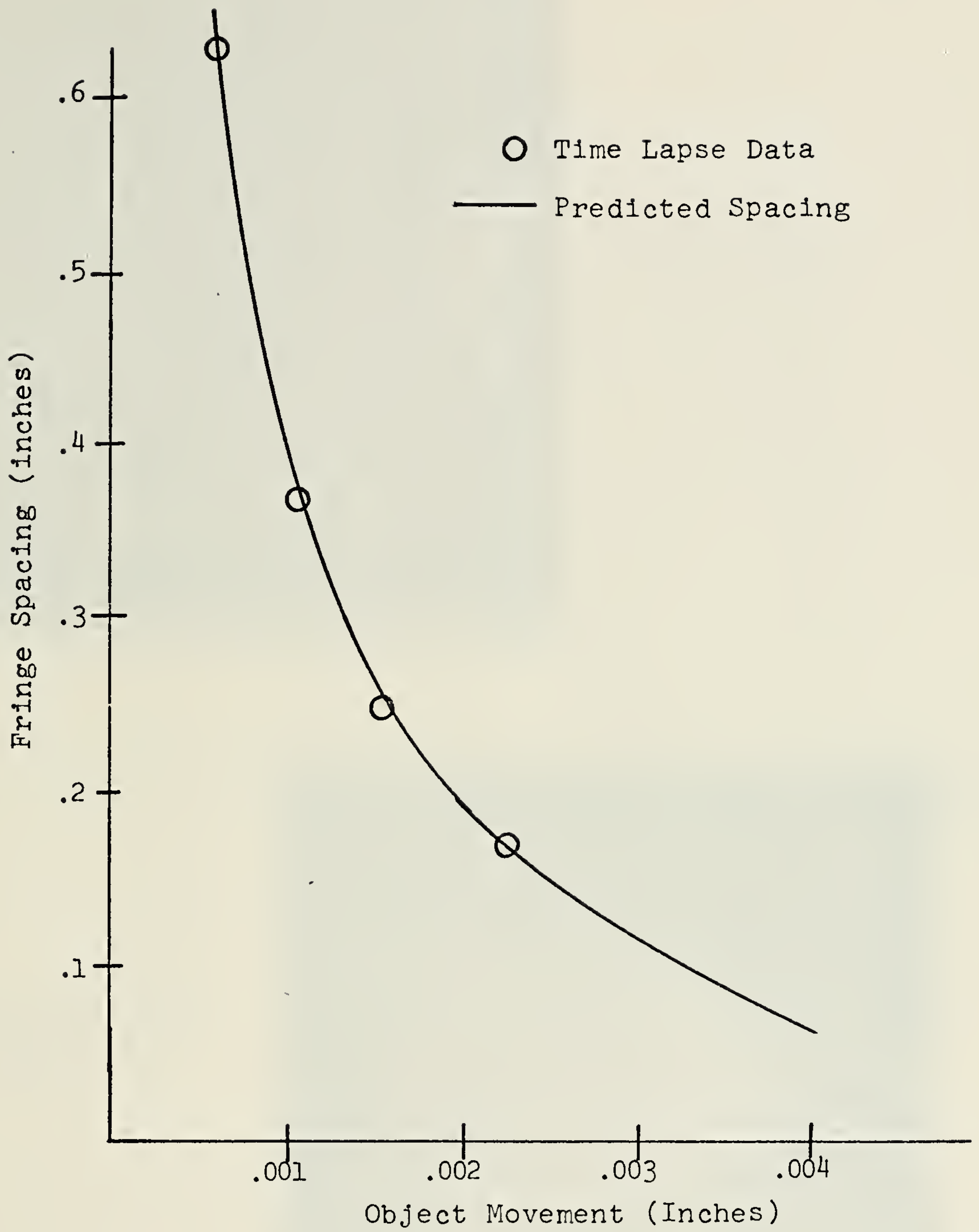
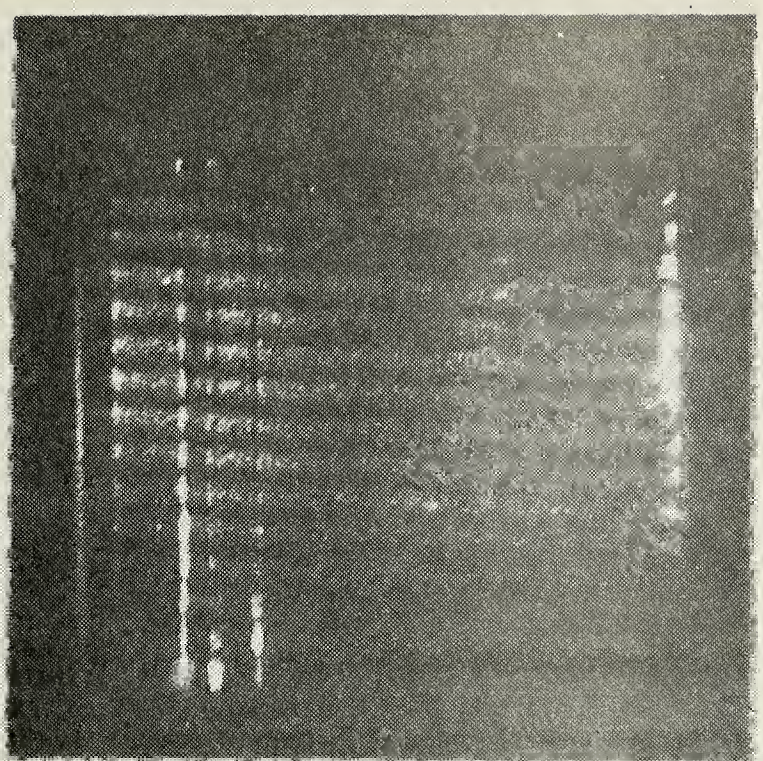
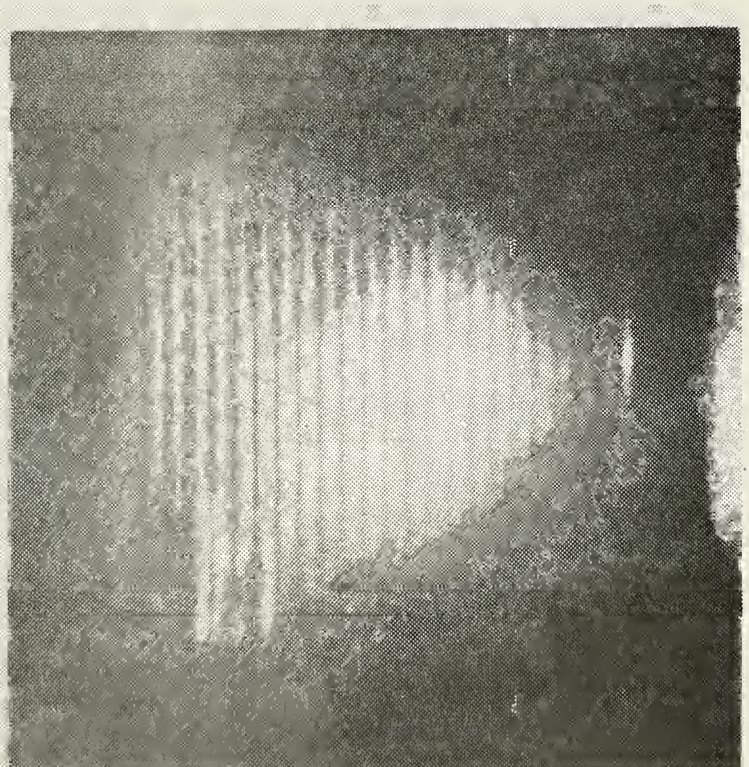


FIGURE 13. Plot of Time Fringe Spacing versus Object Movement



Time Lapse Fringe Spacing Due to Y-Translation



Time Lapse Fringe Spacing Due to X-Translation

FIGURE 14

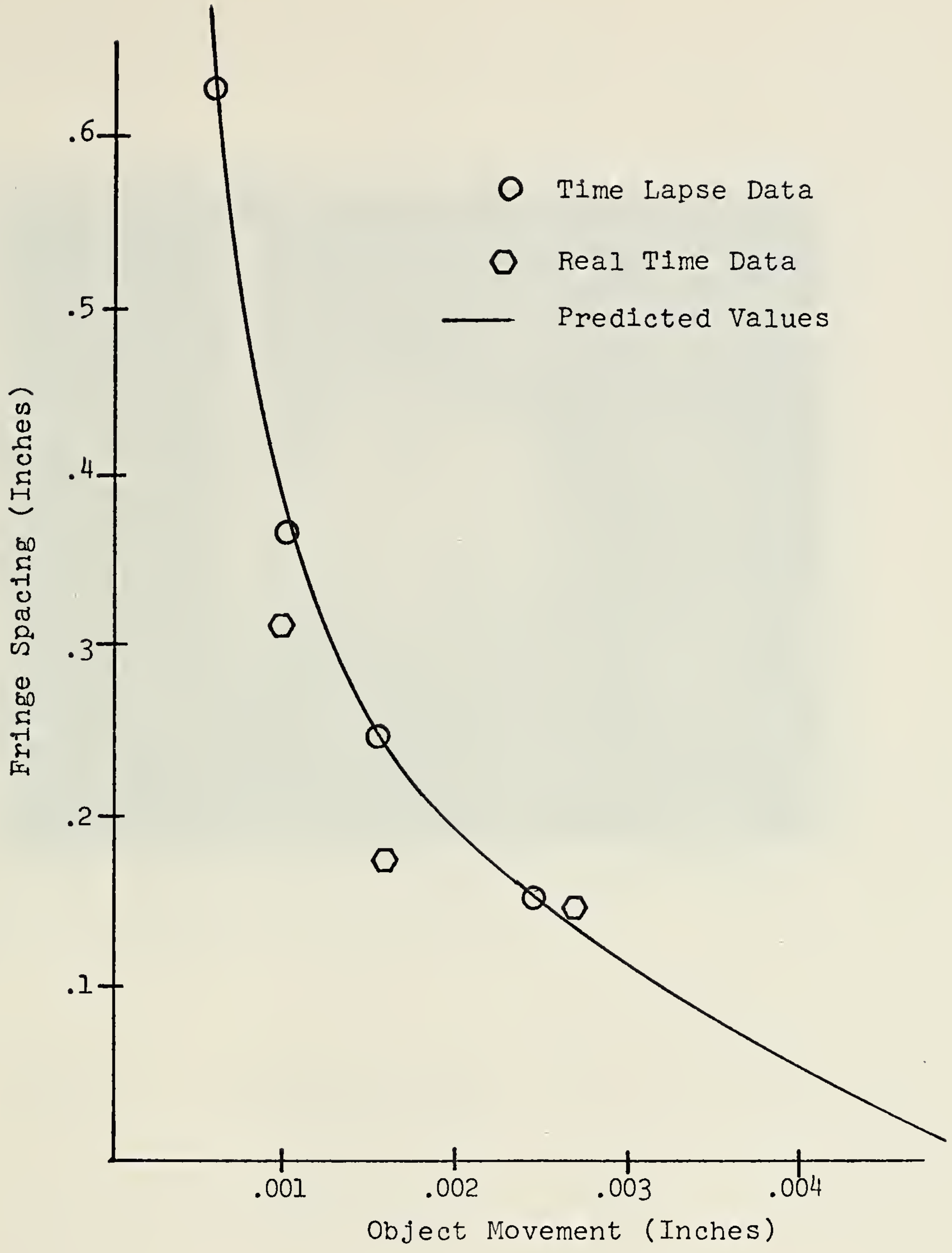


FIGURE 15. Comparative Plot of Real Time and Time Lapse Data

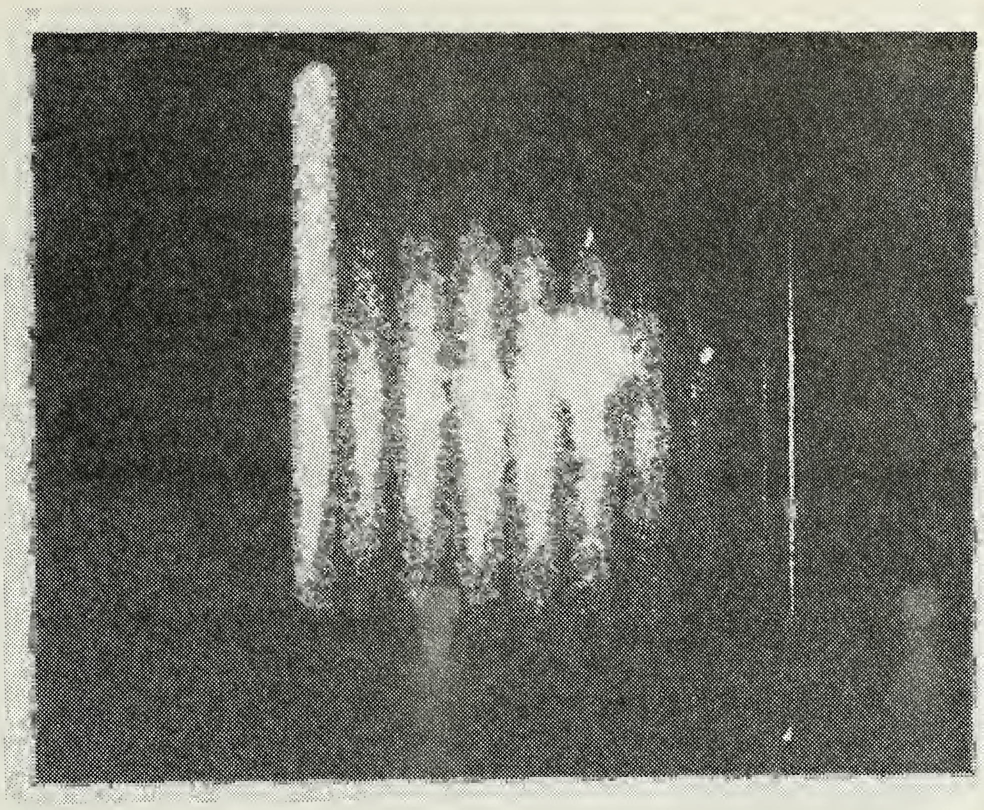


FIGURE 16. Photograph of Real Time Fringes Due to X-Translation

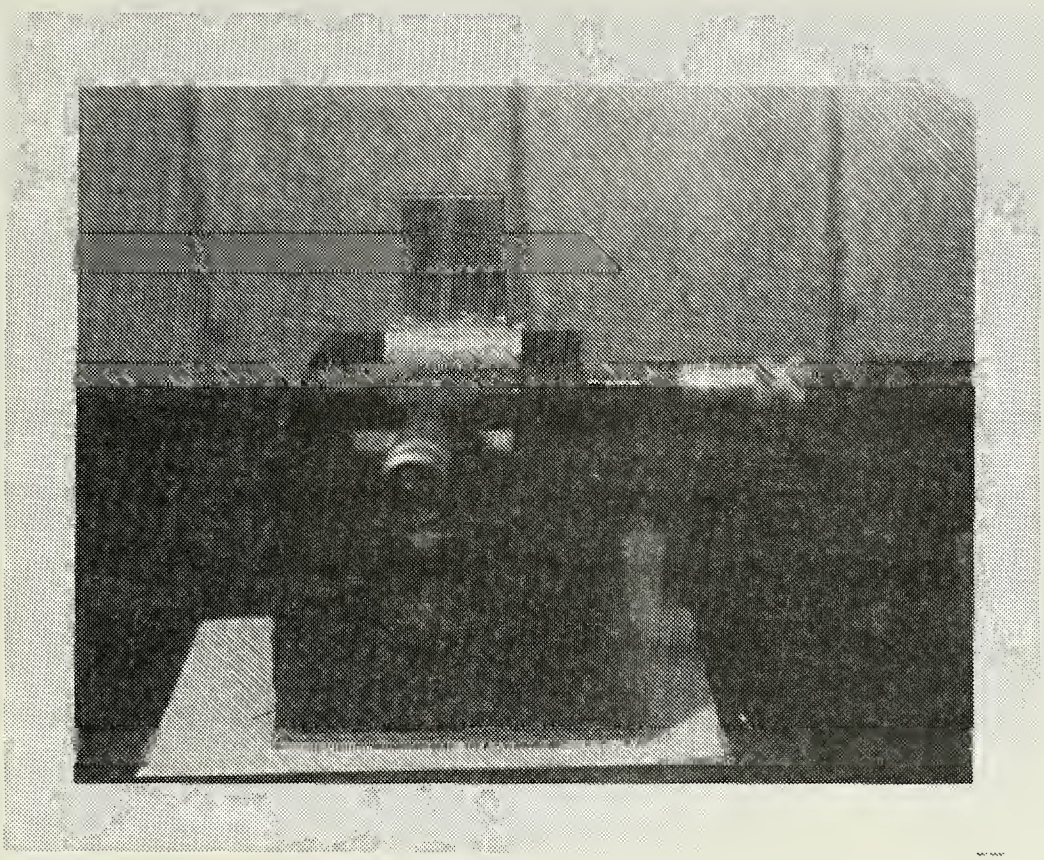


FIGURE 17. X-Y Translating Table Used in Acid Etching Experiments

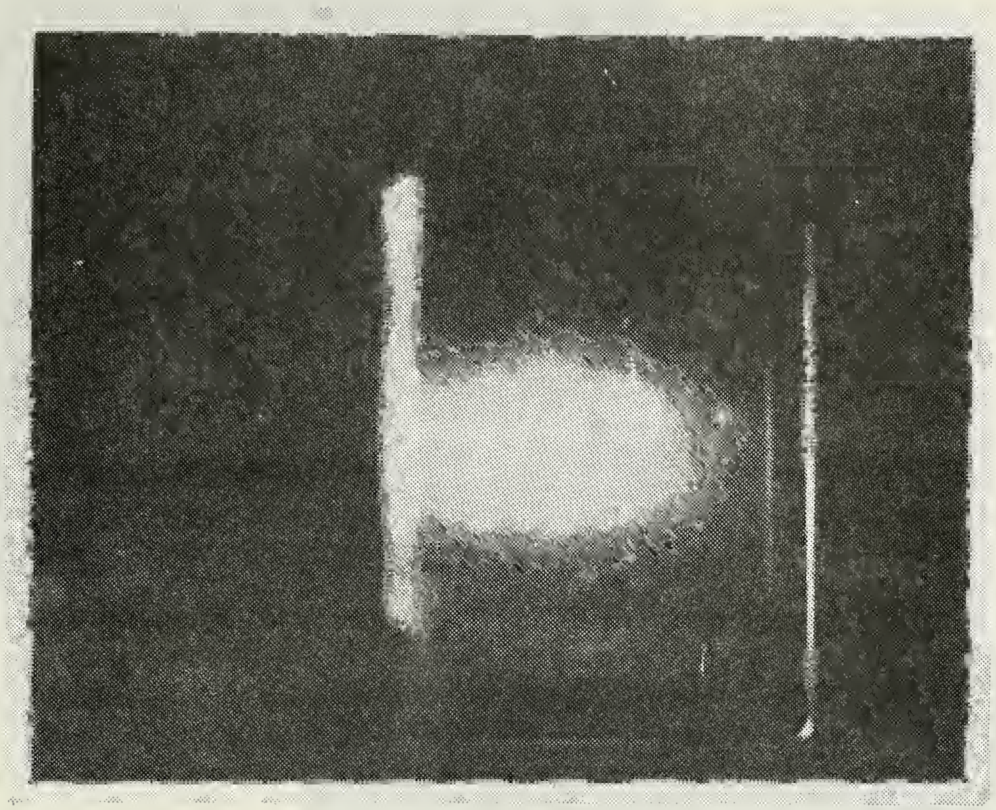
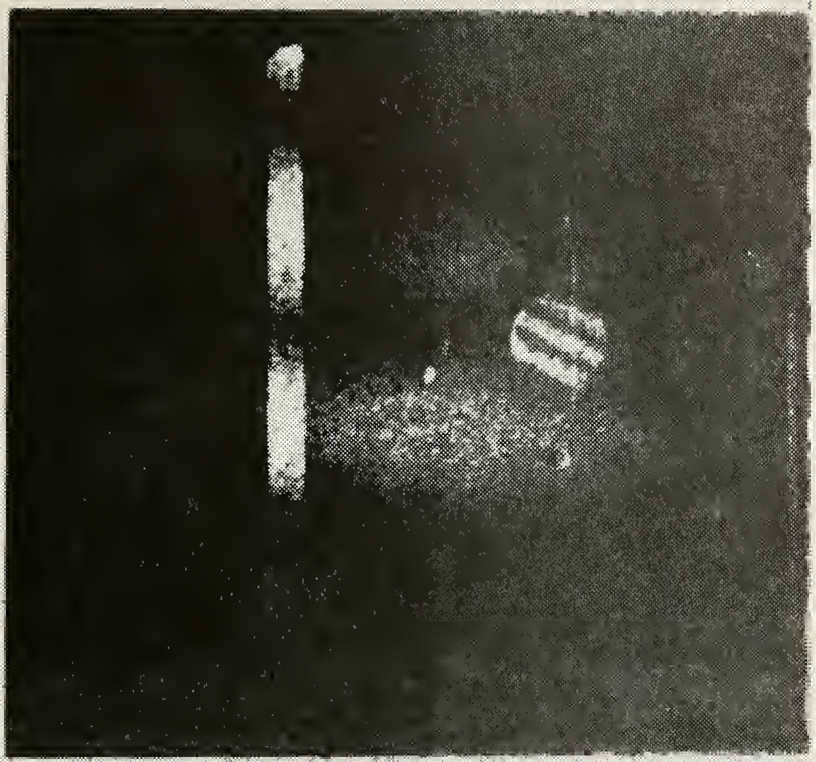


FIGURE 18. Infinite Fringe Starting Point for Z-Translation Experiments



Representative
Fringe Pattern on
Translating Plug
When Voltage Applied

ΔZ = $.40 \times 10^{-4}$ inches

ΔZ = $.70 \times 10^{-4}$ inches

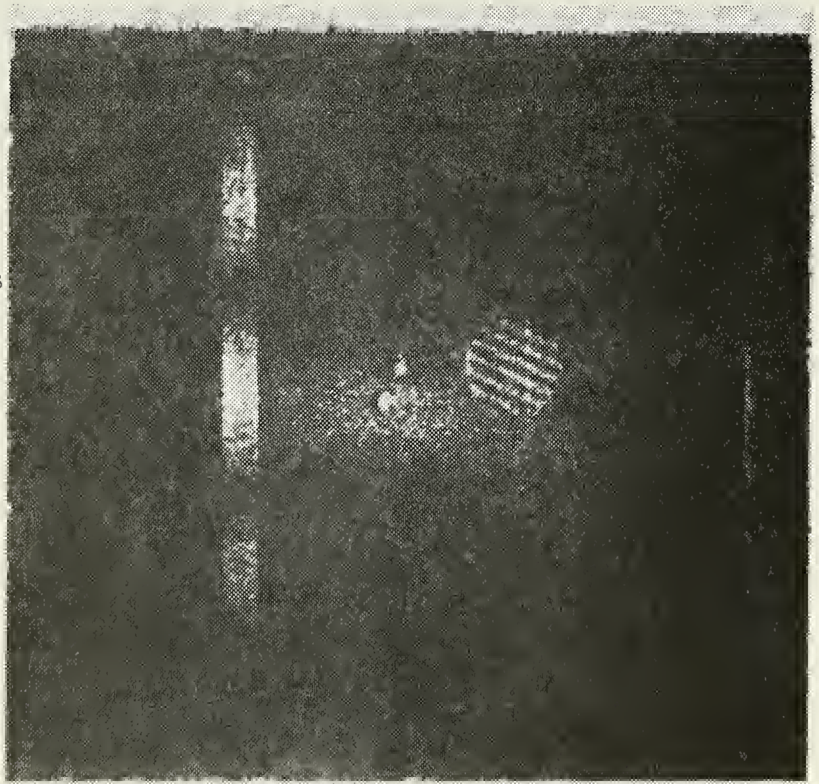
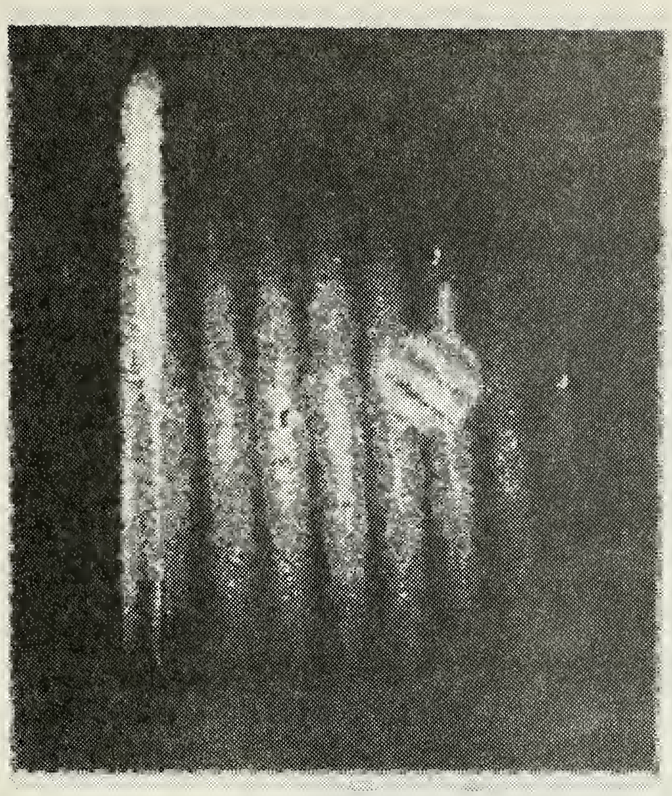
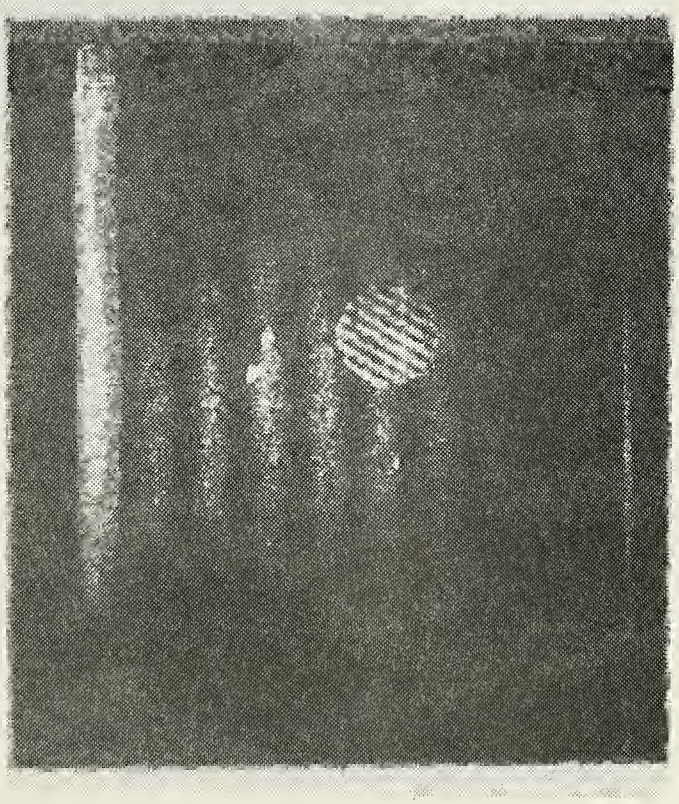


FIGURE 19



$\Delta Z = 1.0 \times 10^{-4}$ inches



Fringe Pattern on Translating Plug with a Known X Displacement Induced

$\Delta Z = 1.8 \times 10^{-4}$ inches

FIGURE 20

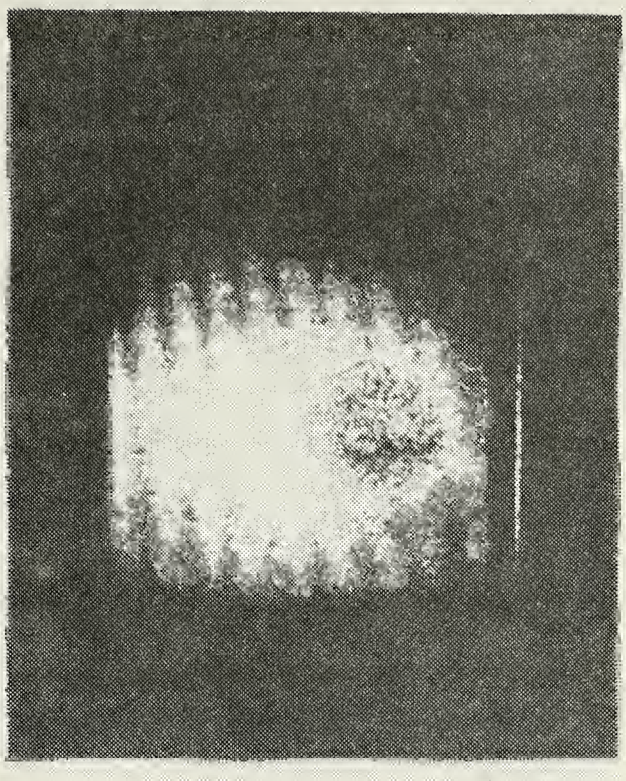


FIGURE 21. Real Time Fringe Pattern Showing Gap Where Paint Layer Has Been Removed

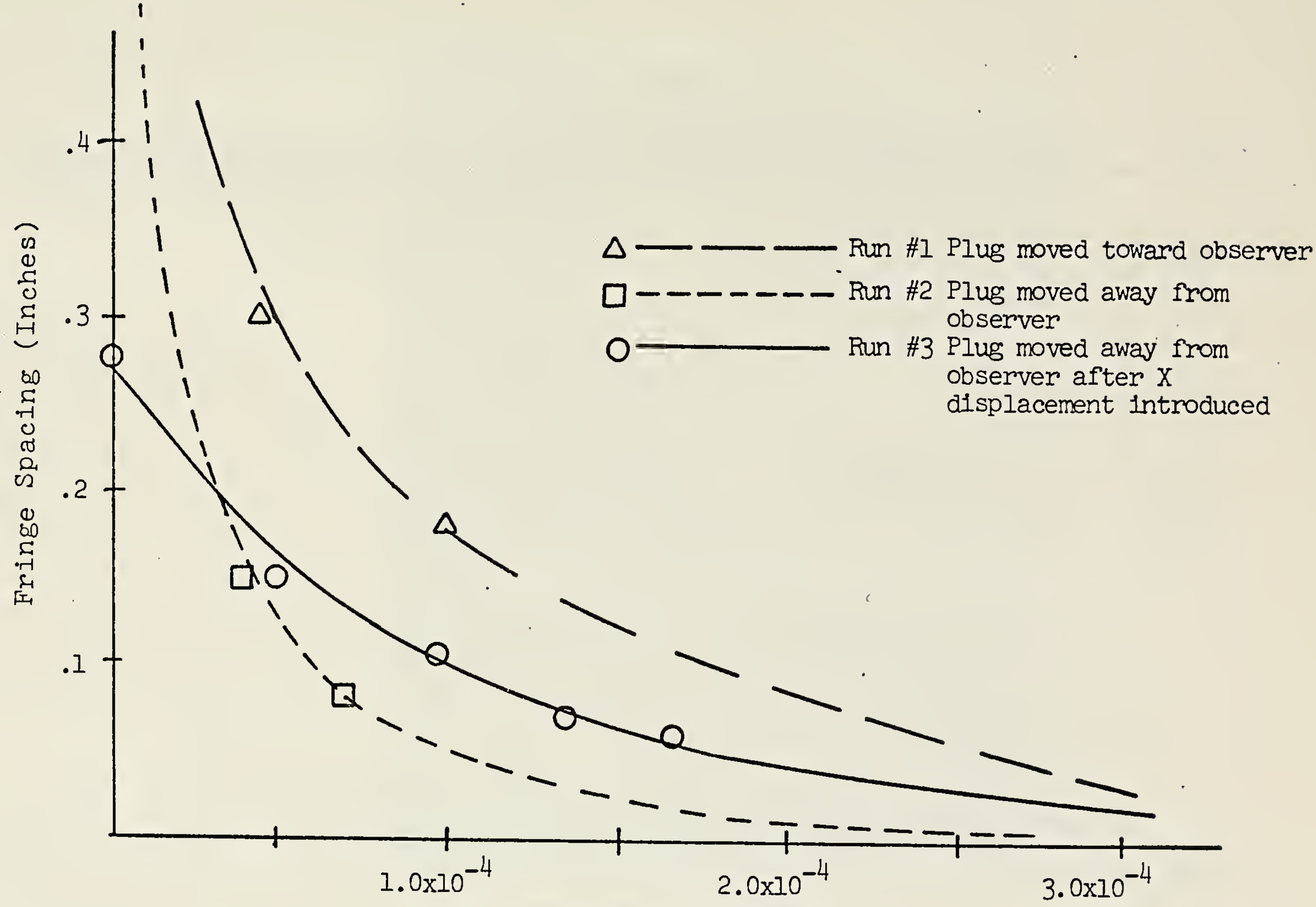


FIGURE 22. Plot of Plug Translation versus Fringe Spacing

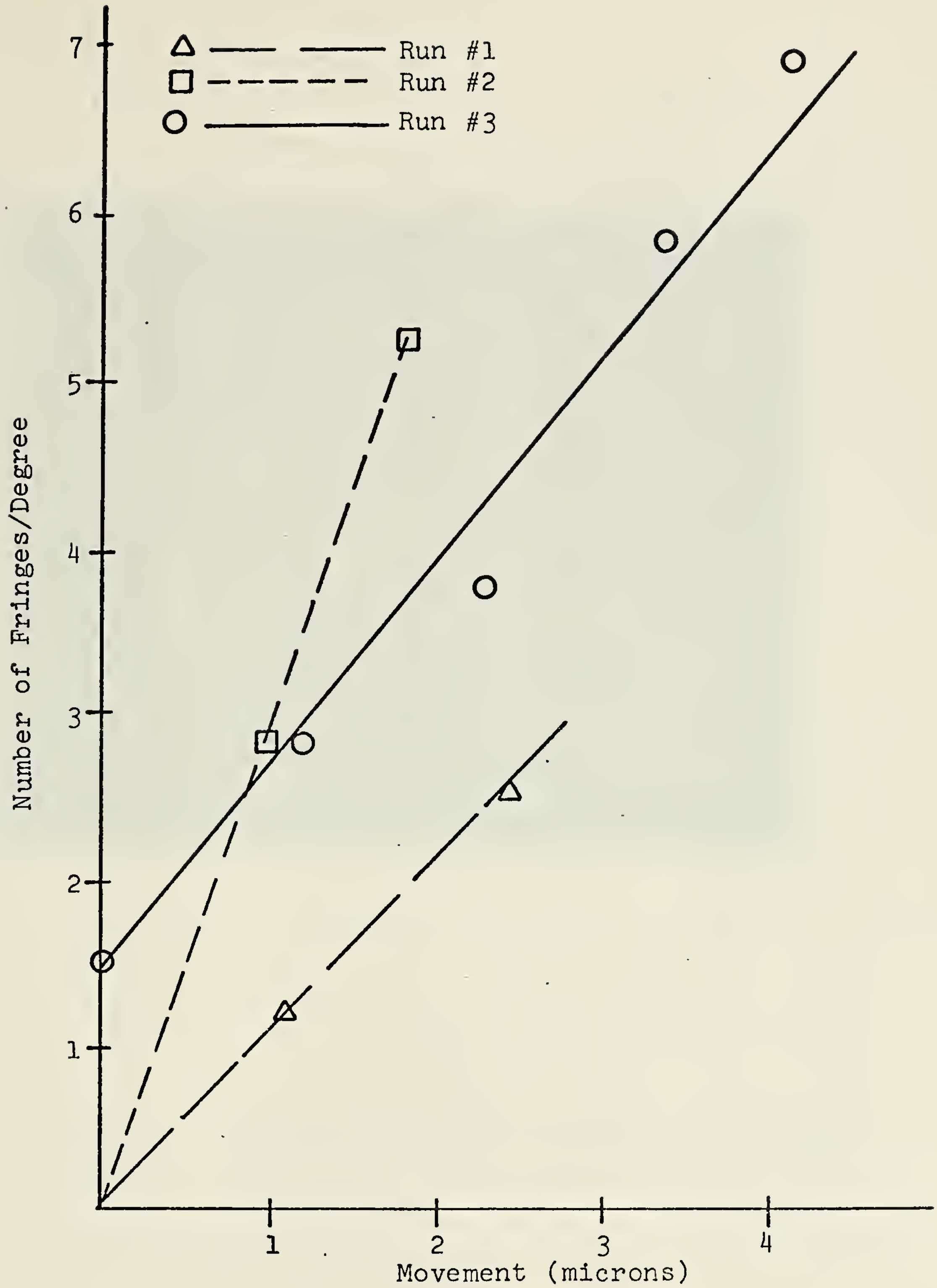


FIGURE 23. Plot of Fringes/Degree versus Plug Movement

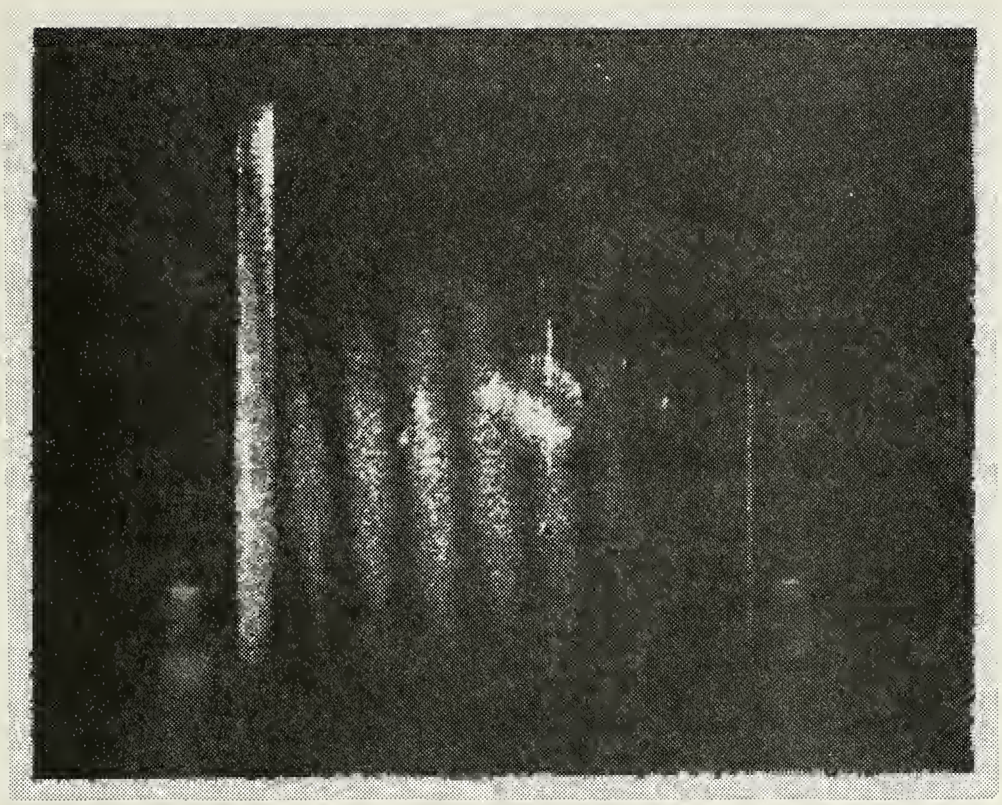


FIGURE 24. Fringe Pattern Introduced on Translating Plug Due to a Known X Translation

APPENDIX A

An Experimental Set Up for Holographic Interferometry of Circular Cylinders

During the course of this investigation, it became apparent that the apparatus for simulating a gun barrel interior would not be required. However, the optics for this set up had already been fabricated using the arrangement of Ennos [2] as a guide. The cylinder length and lens angle were the two parameters felt to be most significant because the entire arrangement was to be mounted on a precision optical bench, where spacing between elements could be easily controlled.

Using the ray tracing matrix techniques described by Biaker [10], a computer program was developed for the Hewlett-Packard 9830 desk computer. The outermost ray of the scene and reference beams were traced through the proposed set up. Each run used a different lens angle or cylinder length. It was determined that a plane concave lens with an angle of seven degrees would produce adequate results if used in conjunction with a cylinder six inches in length. The lens was fabricated from jewelers grade plexiglas and the cylinders were constructed of aluminum, each with an epoxy lining. (These epoxy linings were intended to closely approximate a gun barrel's interior.)

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